Electric Ship Research
at the
University South Carolina

ONR Science and Technology Review
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Associated Faculty

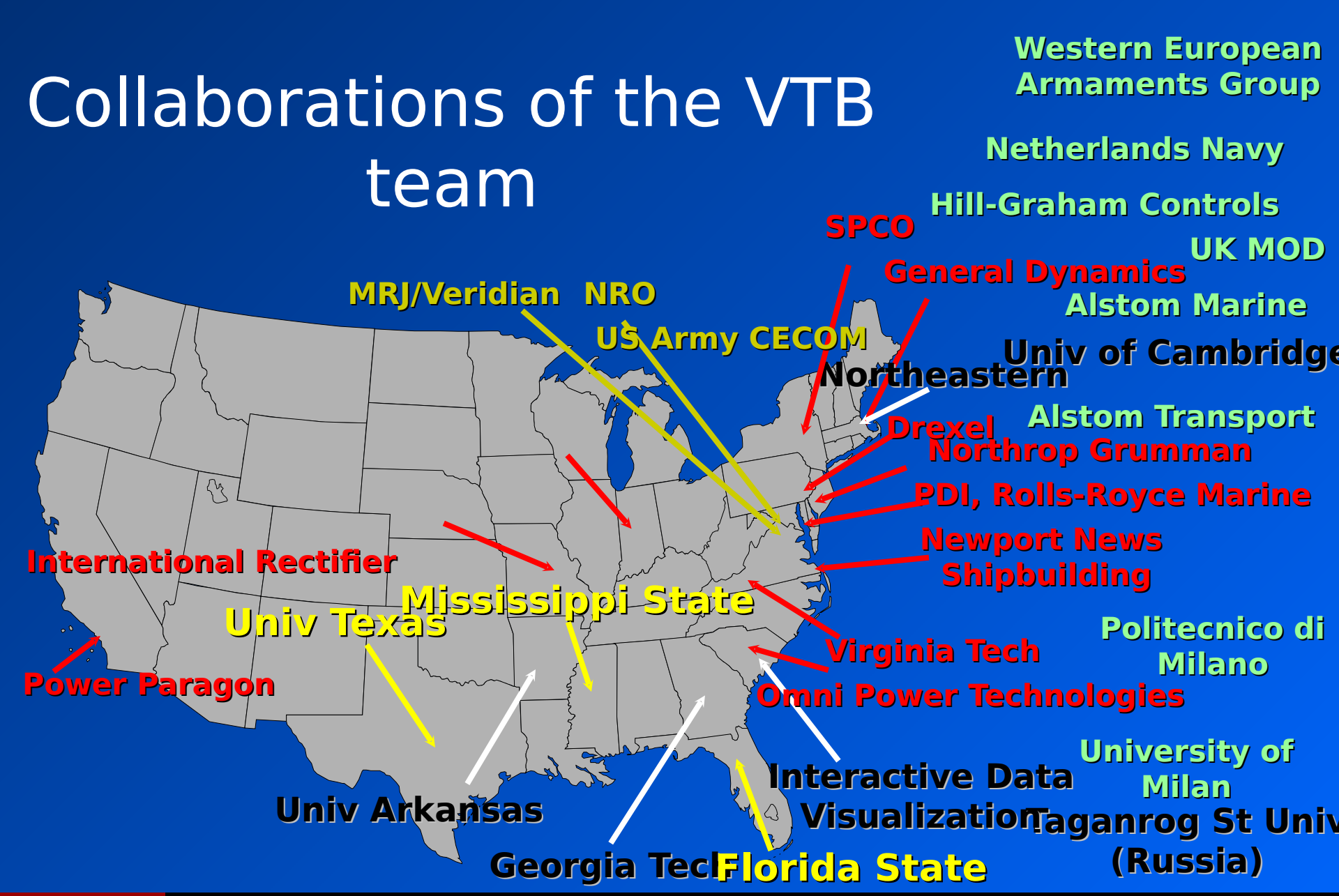
Jerry Hudgins,
Ponci, Jamil
Shengyi Liu,

Plus a whole pile of graduate and undergraduate students who really deserve most of the credit.

Overview of Research Thrusts

- Creating the Virtual Test Bed (VTB) environment for interdisciplinary ship systems
- Power system architecture assessments focusing on zonal robustness
- Control system studies, focusing on control prototyping and validation, and application of manifold-based techniques for hierarchical control strategies

Collaborations of the VTB team



Virtual Prototyping Environment

- Further development of VTB
- Realtime/distributed environment that supports hardware in the loop
- Model tools
- Advanced solver methods
- Security of the simulation environment
- Simulation under uncertainty

Design of mobile electric power systems requires an interdisciplinary approach

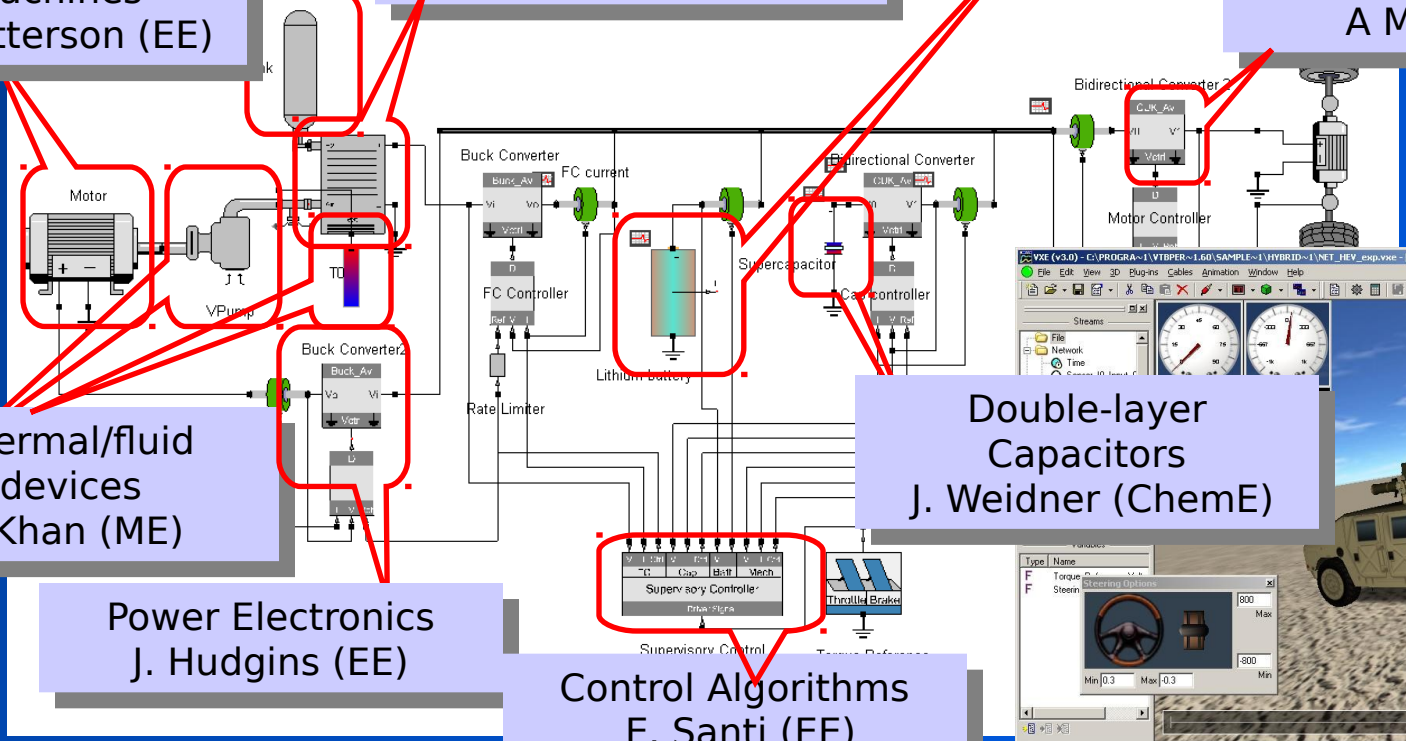
H2 storage
J. Ritter (Chem E)

Lithium Battery
B. Popov (ChemE)

Advanced Machines
D. Patterson (EE)

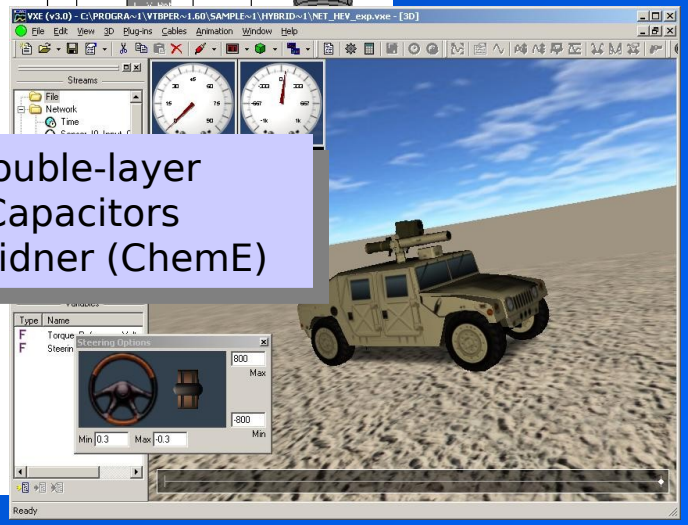
PEM FC
J. Van Zee, (ChemE)

Motor Drives
A Monti (EE)



Thermal/fluid devices
J. Khan (ME)

Double-layer Capacitors
J. Weidner (ChemE)

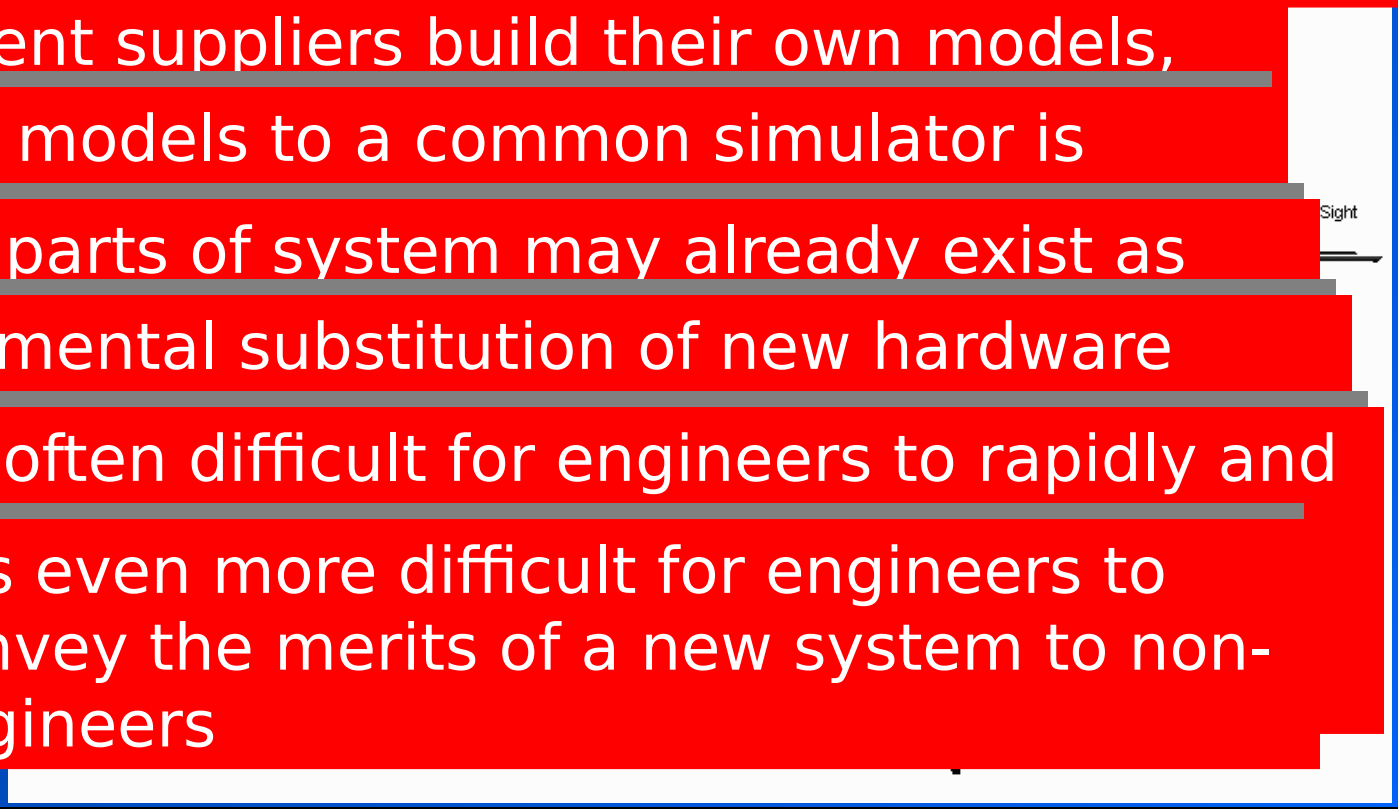


Power Electronics
J. Hudgins (EE)

Control Algorithms
E. Santi (EE)

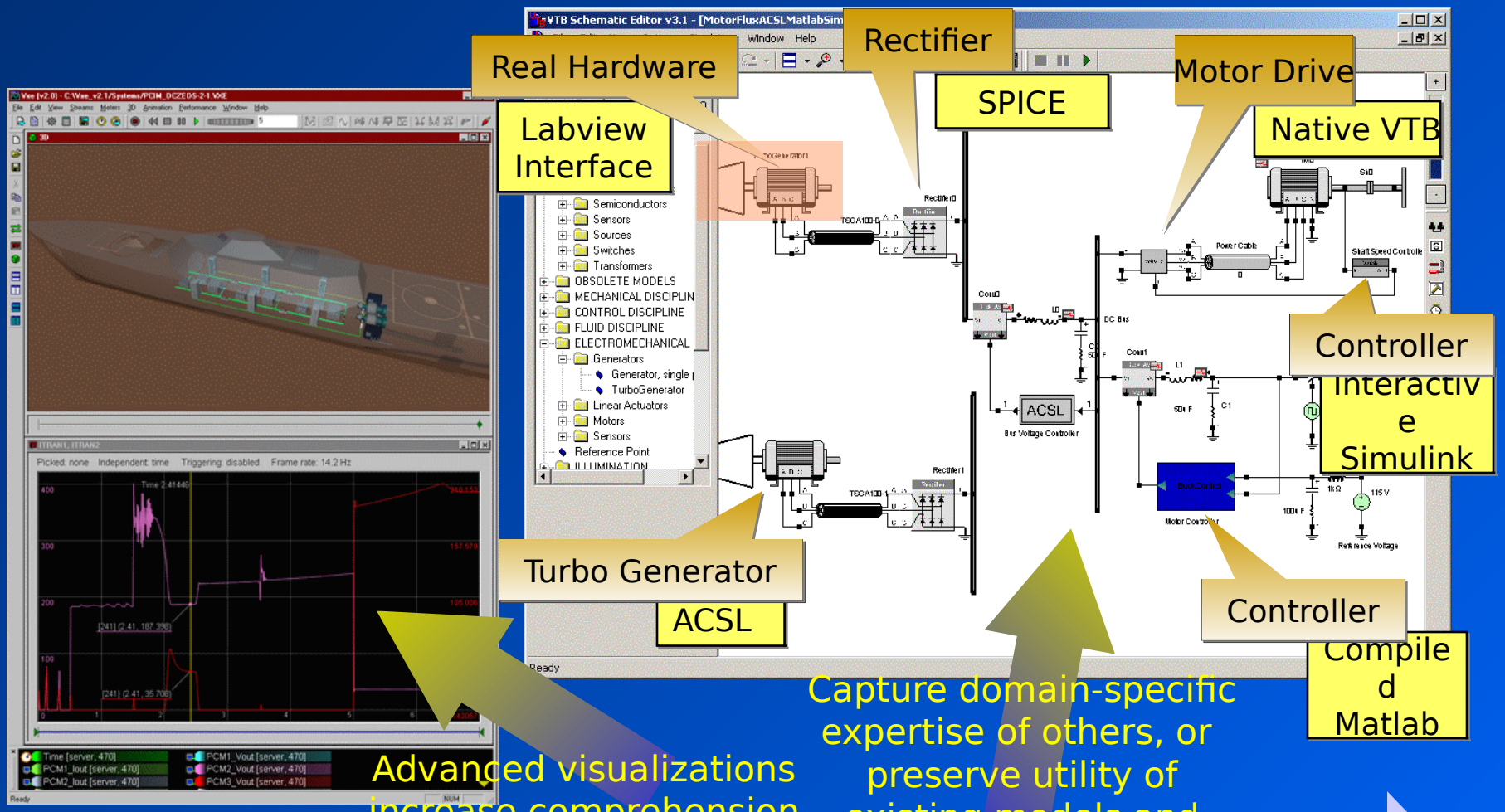
Motivation for a VTB

- Complex systems bridge technical disciplines
- Different disciplines use different design/simulation tools
- Different analysts seek different information from a mo
- Component suppliers build their own models,
- Porting models to a common simulator is
- Some parts of system may already exist as
- Incremental substitution of new hardware
- It is often difficult for engineers to rapidly and
- It is even more difficult for engineers to convey the merits of a new system to non-engineers



We have been building a VTB that is expected to…

- Accelerate the testing of system concepts
- Rapidly integrate the work of many team members, across many disciplines
- Allow many formalisms for model expression
- Be highly interactive and intuitive
- Allow incremental migration from concept to proven realization



Virtual Test Bed

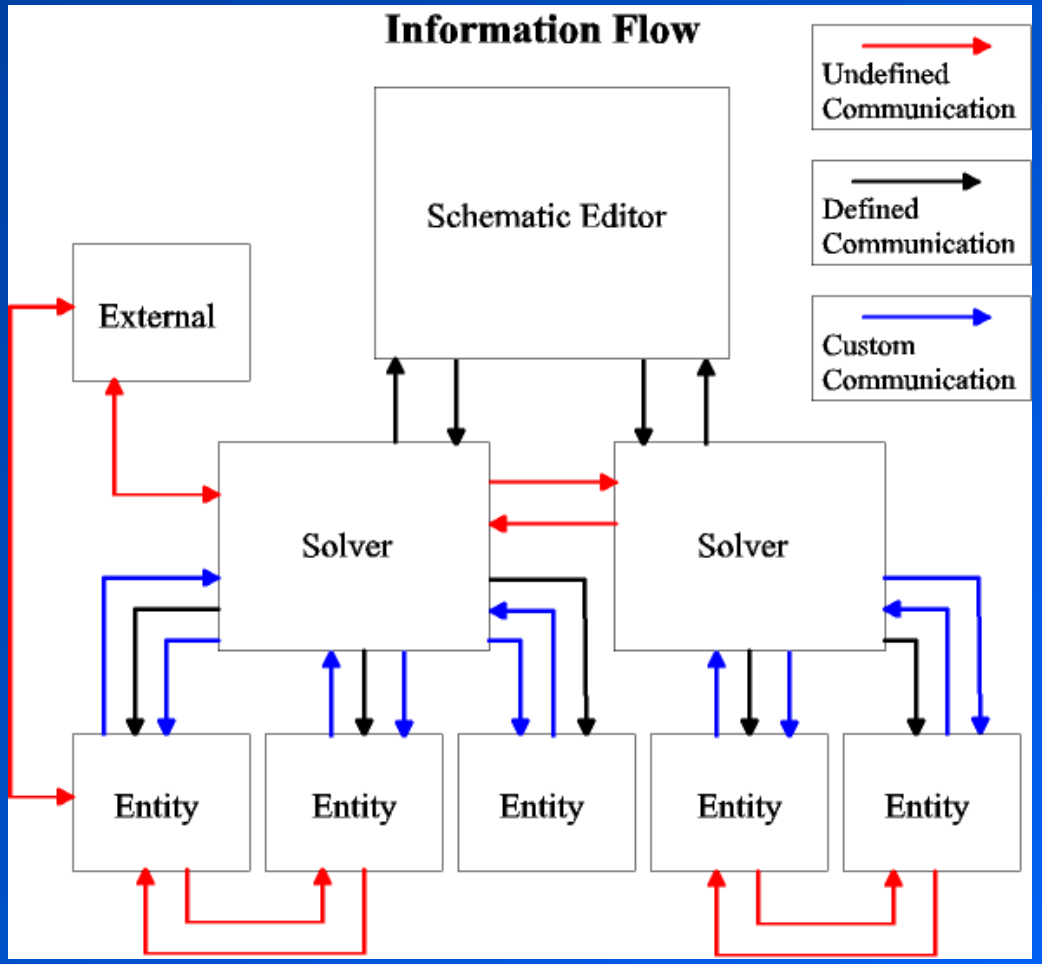
- Provides the environment for integrating the work of interdisciplinary teams
- Provides a “common language” for expression of problems and solutions
- Enables virtual prototyping and tuning of complex dynamic systems

Salient Accomplishments

- Release of VTB2002
- Variable time steps in independent mixed-model cosimulation environment
- Hierarchical grouping of components
- Multiple-layer models (both computational and graphic)
- New solvers - user selectable
- Better support for cosimulation objects

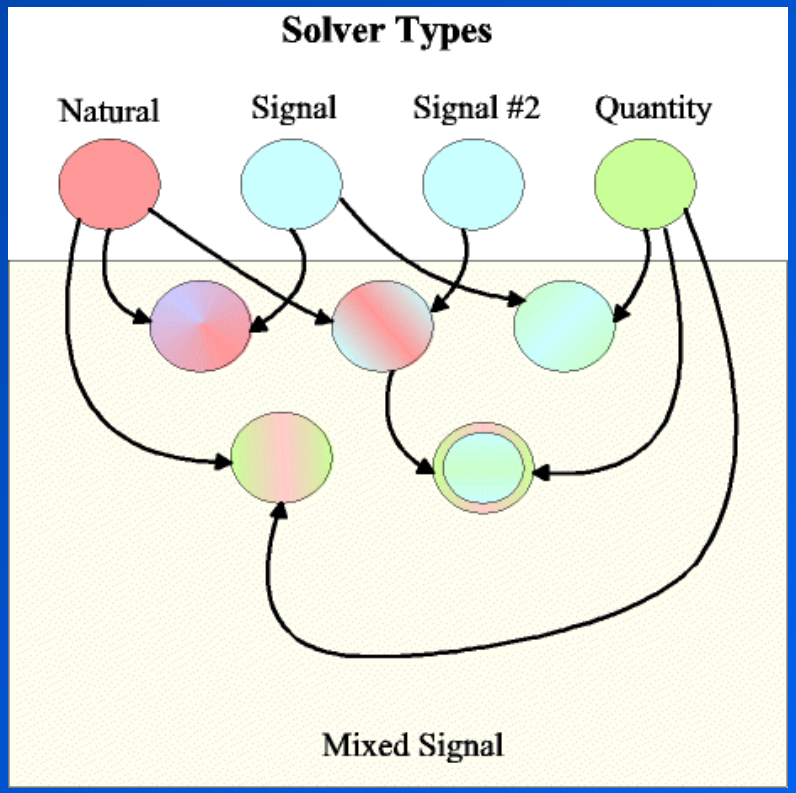
New Software Architecture

- Block Communication
  - Solver base class
  - Solver custom class
  - Entity base class
- Feedback class
- External Communication



Architecture Advances

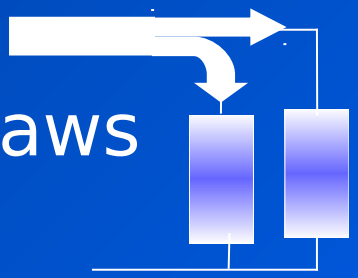
- Environment supports multiple solvers
- Interpretation of model connectivity is solver-specific
- Multiple forms of connectivity are possible
- Solvers support simulation of mixed-signal systems



VTB supports all three types of object couplings, even for imported and hardware objects

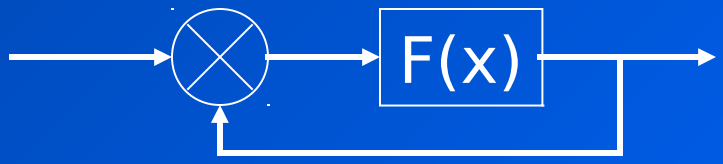
Natural Coupling

Enforce physical conservation laws



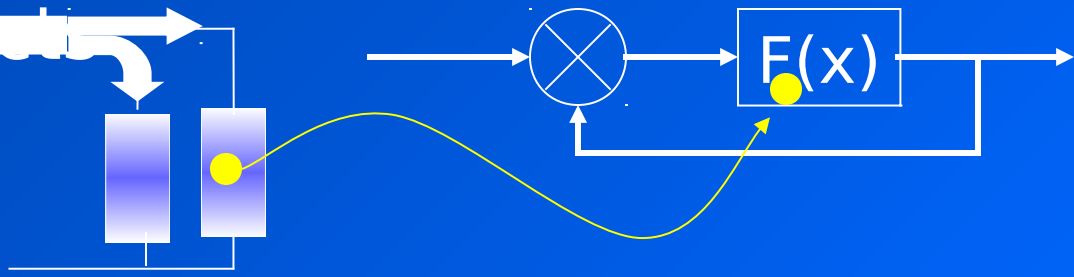
Signal Coupling

Directed flow of information through objects



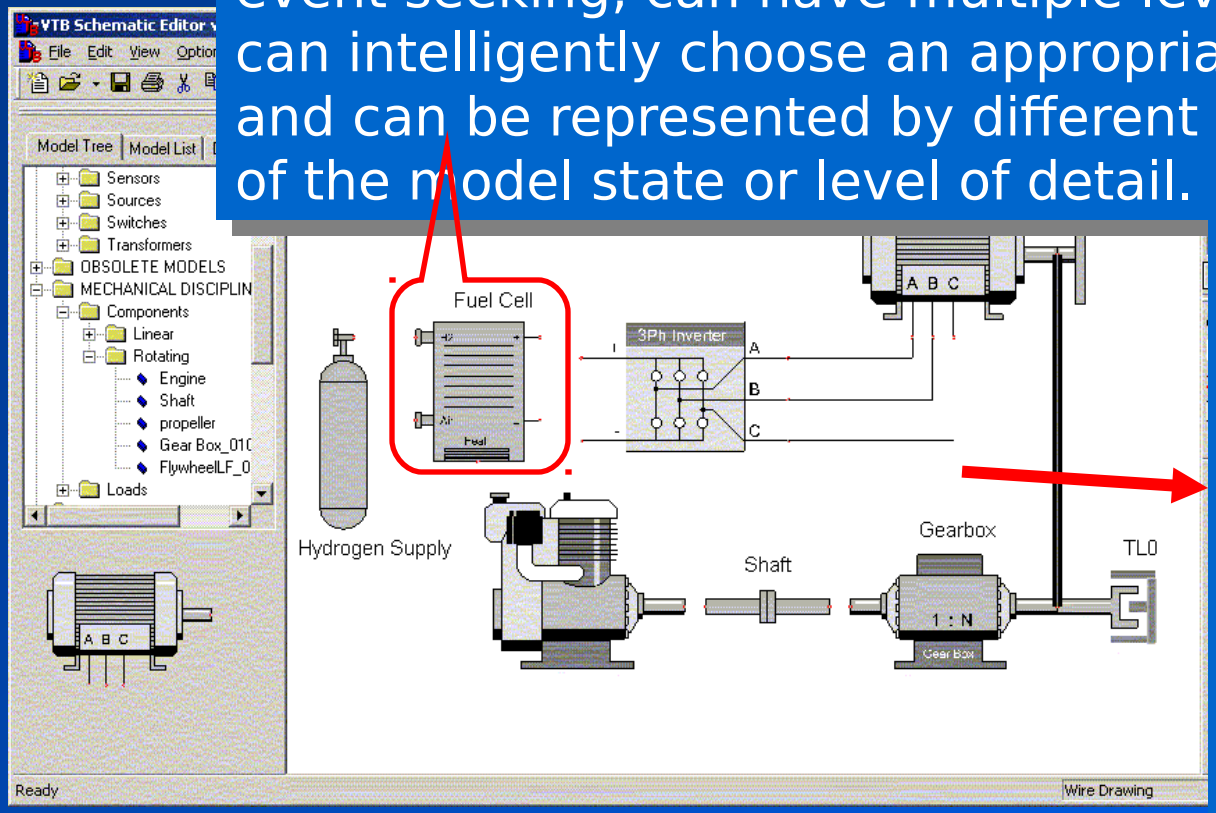
Data Coupling

Pass data between objects



Independent Model Format

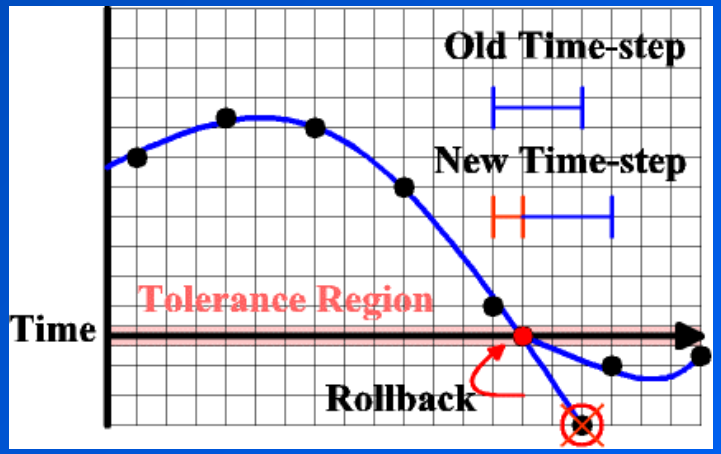
Models are independent entities that can have their own solution methods, can run as cosimulation objects, can independently control time stepping or event seeking, can have multiple levels of detail and can intelligently choose an appropriate level of detail, and can be represented by different icons as a function of the model state or level of detail.



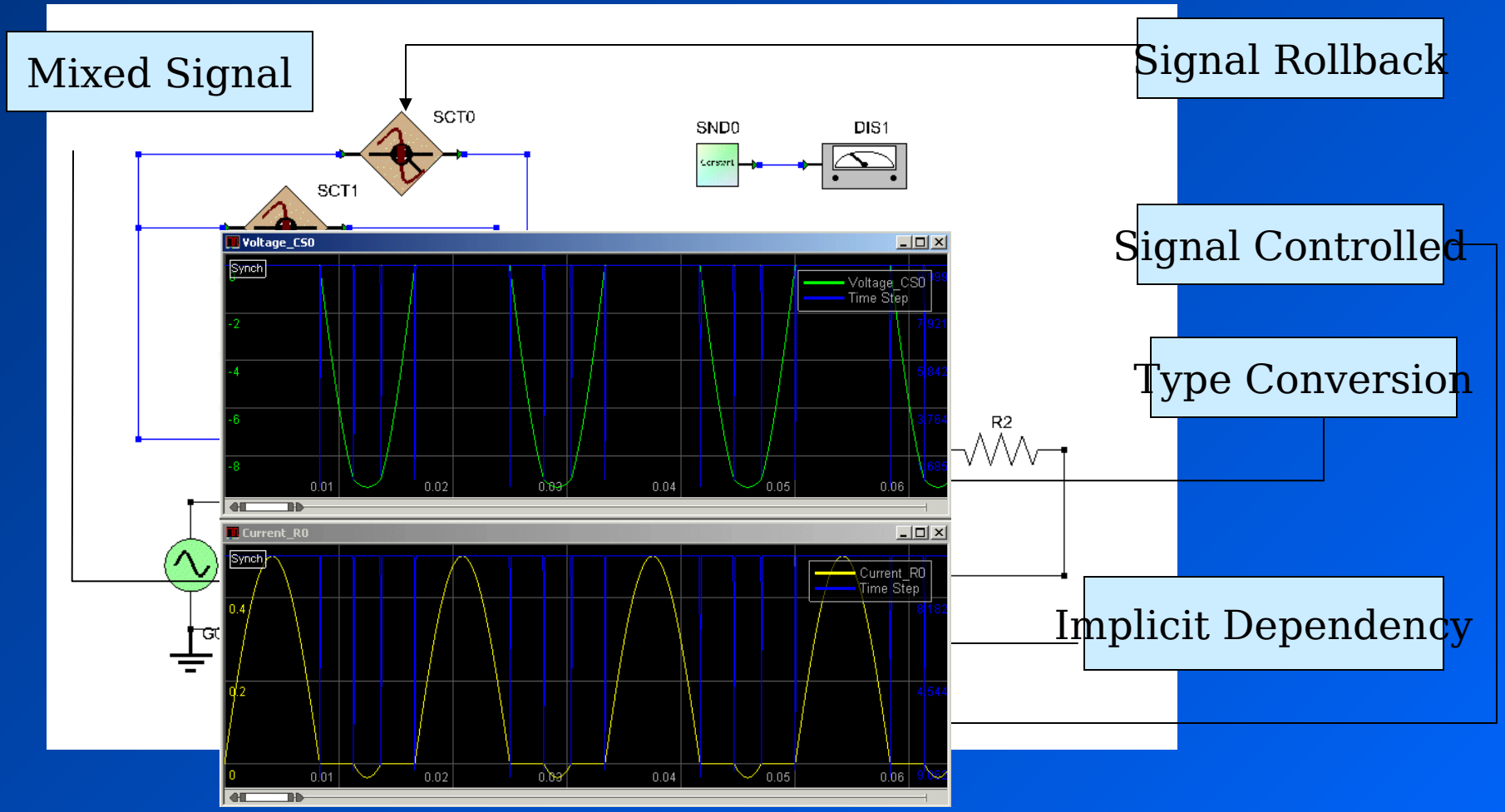
Native models with Natural connections give their Jacobian to the network solver. Other means may be used to resolve natural coupling contraints for cosimulation or hardware objects.

New Natural/Signal Solver

- Models can control time-step
  - Set arbitrary step size
  - Predict events
  - Rollback to previous state
- Discrete-Event window
- Inner-schematic dependencies
- True initial conditions

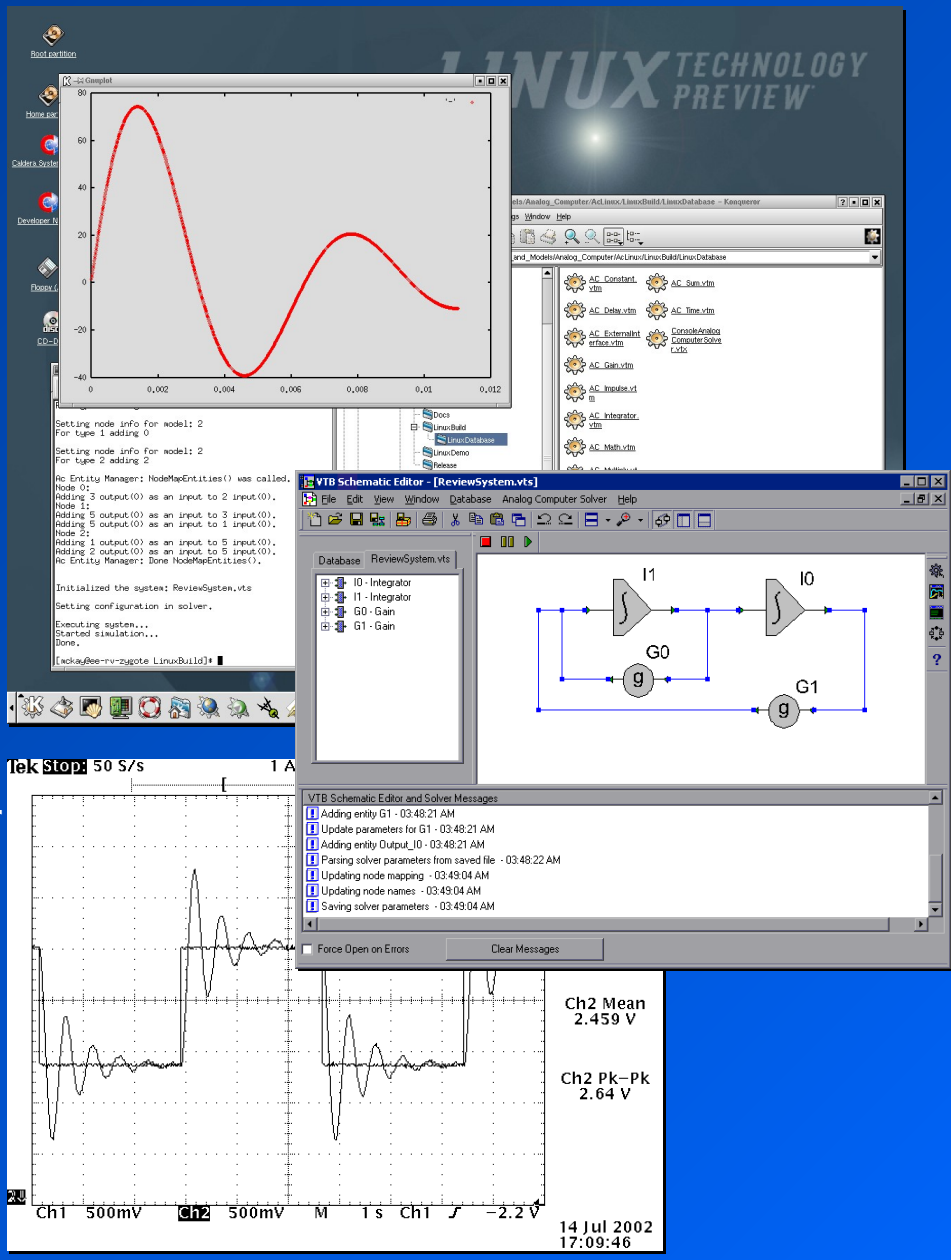


Example (Mixed Signal)



Alternate Solver for independent signal blocks

- Supports Realtime operation
- Fast and Scalable
- Linear Time Complexity
  - Matrix techniques scale super-linearly with time
- Handles both non-linear and linear systems
- Highly configurable for realtime or hardware in the loop operations
- Available for Linux


LINUX TECHNOLOGY PREVIEW
VTB Schematic Editor - [ReviewSystem.vts]
File Edit View Window Database Analog Computer Solver Help
Database ReviewSystem.vts
I0 - Integrator
I1 - Integrator
G0 - Gain
G1 - Gain
I1
I0
G0
G1
VTB Schematic Editor and Solver Messages
Adding entity G1 - 03:48:21 AM
Update parameters for G1 - 03:48:21 AM
Adding entity Output_I0 - 03:48:21 AM
Parsing solver parameters from saved file - 03:48:22 AM
Updating node mapping - 03:49:04 AM
Updating node names - 03:49:04 AM
Saving solver parameters - 03:49:04 AM
Force Open on Errors
Clear Messages
Tek Stop: 50 S/s
Ch2 Mean
2.459 V
Ch2 Pk-Pk
2.64 V
Ch1 500mV Ch2 500mV M 1 s Ch1 -2.2 V
14 Jul 2002
17:09:46

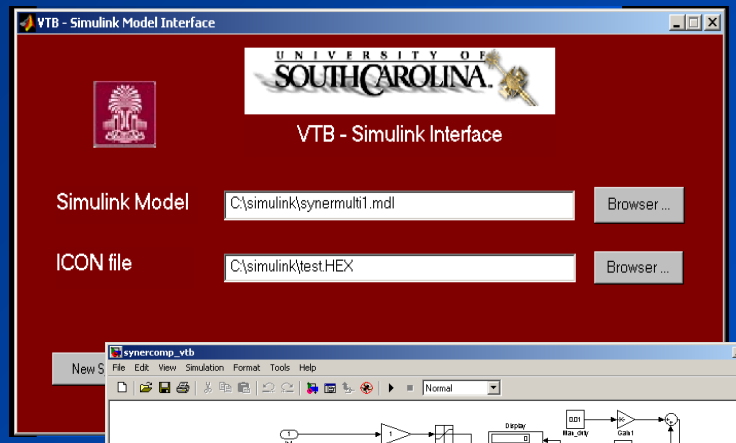
Tools for Model Building

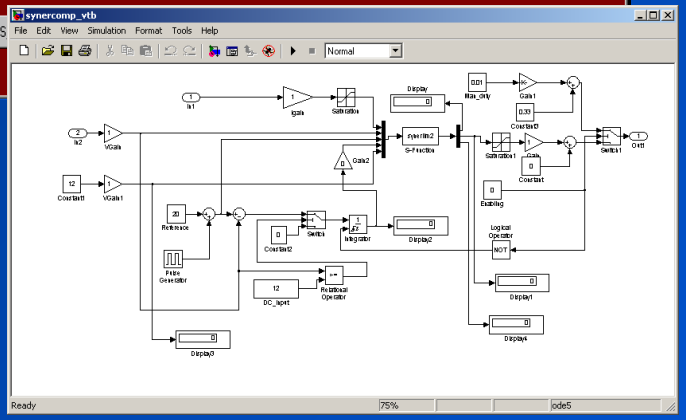
Import models from Simulink

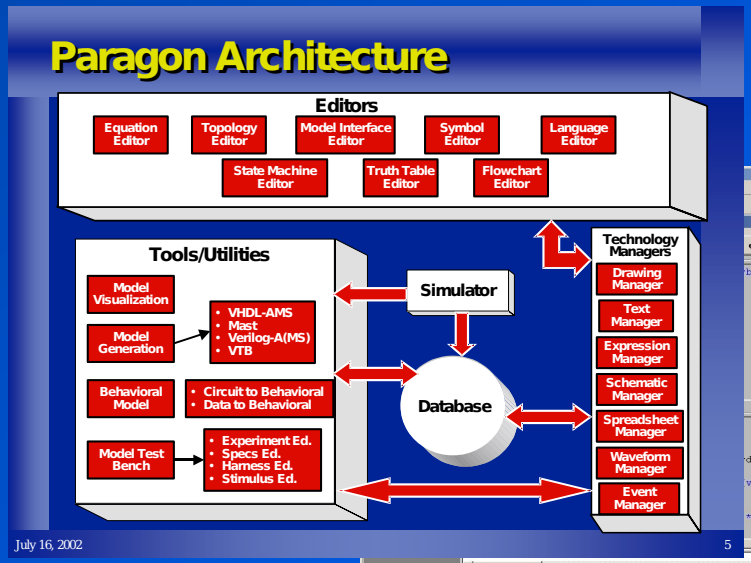
- with Natural or signal coupling
- including S functions or C code

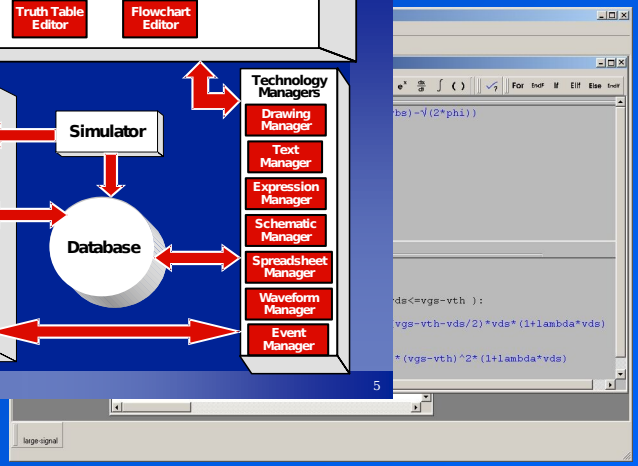
Import models to/from VHDL-AMS

Graphical model generation tool from user-defined









$$v_{as}(t) - v_{ns}(t) = r_{as} i_{as}(t) + \frac{d}{dt}\lambda_{as}(t)$$

$$v_{bs}(t) - v_{ns}(t) = r_{bs} i_{bs}(t) + \frac{d}{dt}\lambda_{bs}(t)$$

$$v_{cs}(t) - v_{ns}(t) = r_{cs} i_{cs}(t) + \frac{d}{dt}\lambda_{cs}(t)$$

$$i_{ns}(t) = -(i_{as}(t) + i_{bs}(t) + i_{cs}(t))$$

$$0 = r_{ar} i_{ar}(t) + \frac{d}{dt}\lambda_{ar}(t)$$

$$0 = r_{br} i_{br}(t) + \frac{d}{dt}\lambda_{br}(t)$$

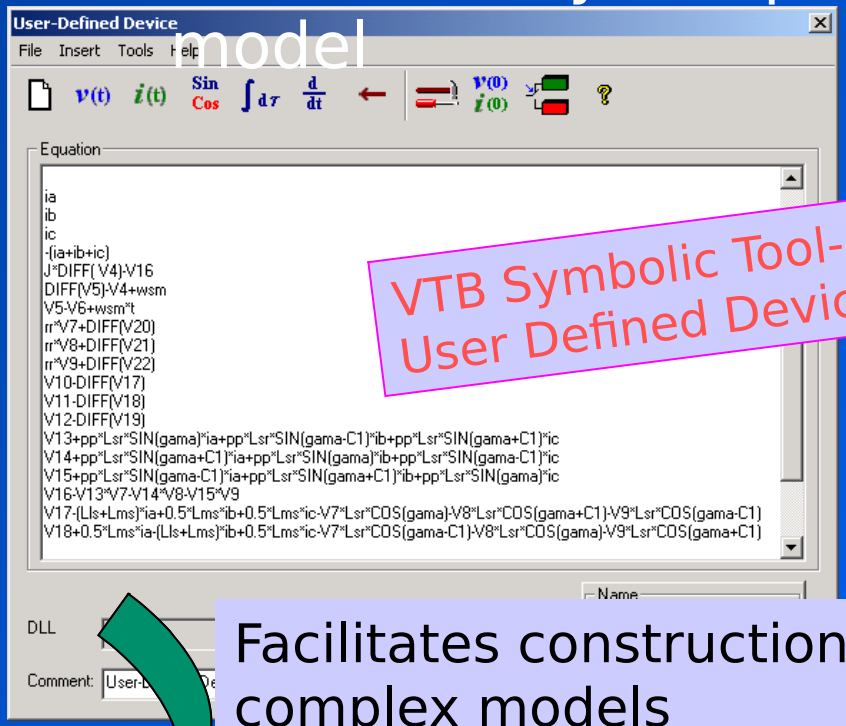
$$0 = r_{cr} i_{cr}(t) + \frac{d}{dt}\lambda_{cr}(t)$$

$$J\frac{d\omega_m(t)}{dt} = (i_{abcs}(t))^T \left[\frac{\partial L_{sr}(t)}{\partial \theta_m}\right] i_{abcr}(t) + T_m(t)$$

$$\frac{d\theta_m(t)}{dt} = \omega_m(t)$$

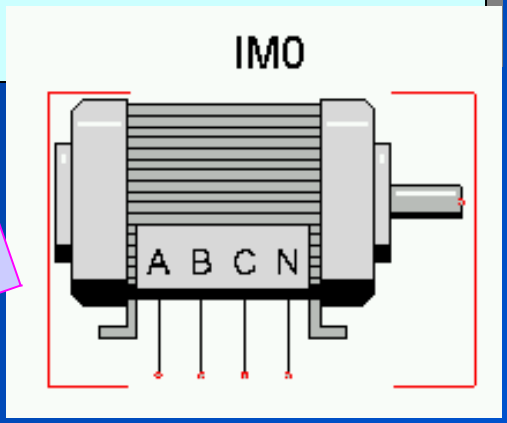
Model Equations

User Defined Device, using symbolic compiler to generate Jacobian and automatically compile model



VTB Symbolic Tool-User Defined Device

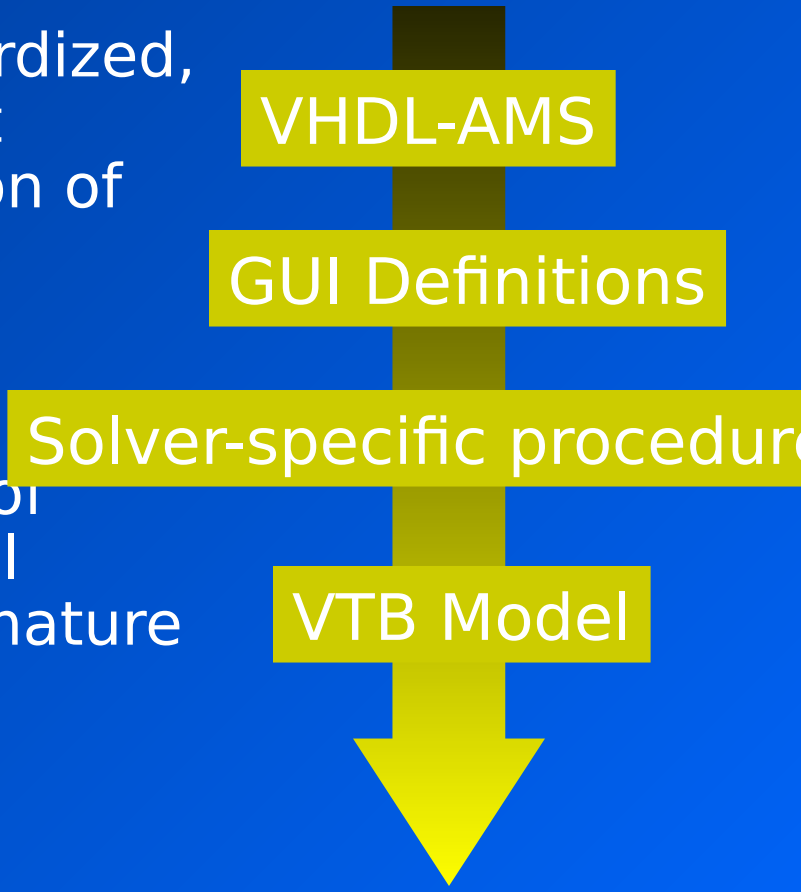
VTB DLL Model



Facilitates construction of complex models containing nonlinearities and many equations

VHDL-AMS

- VHDL-AMS is a recent IEEE-standardized, solver-independent, language that supports description and simulation of interdisciplinary systems
- Tools aid compilation of VHDL-AMS descriptions into model
- VHDL-AMS is a reasonable choice of archive language to support model migration as solver technologies mature



“The Model is the Spec”

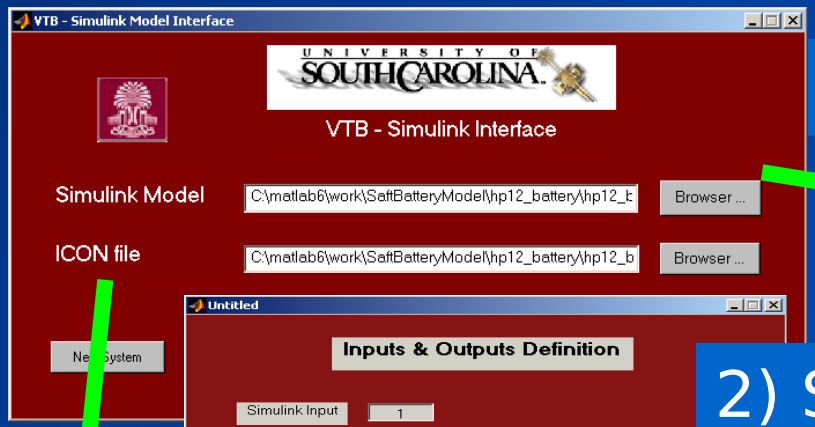
Taking SBA one step further…

VHDL-AMS

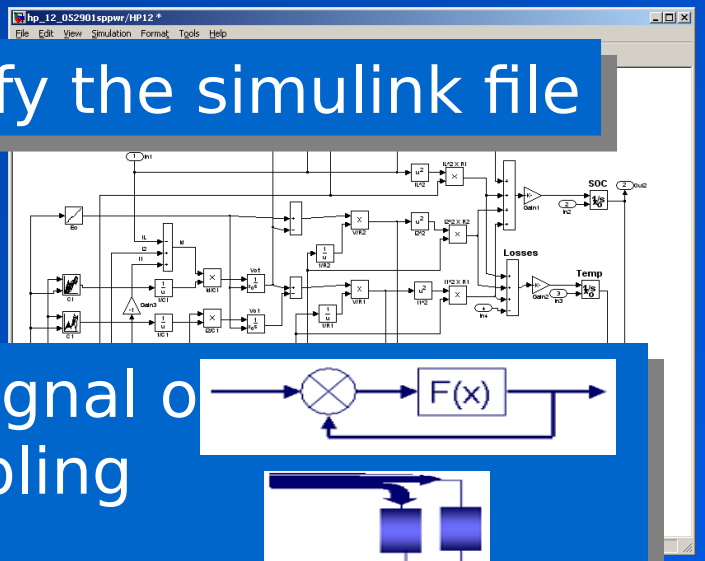
Hardware Description Language

Note that VHDL-AMS is not a modeling language per se, but rather a way to describe real things. If a simulation model is based on the hardware description, then the simulation model can become the performance specification for the system component

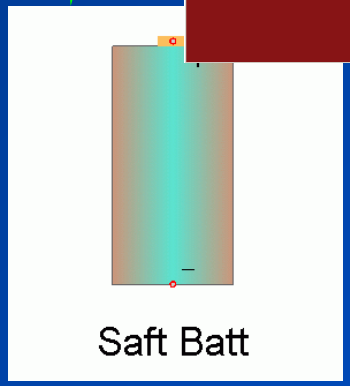
Fast wrapping of non-native models

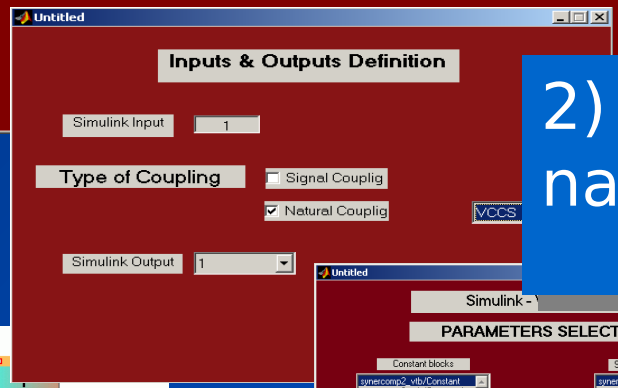


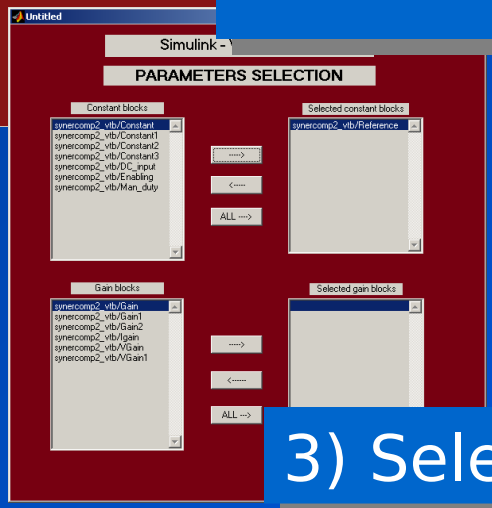
1) Identify the simulink file

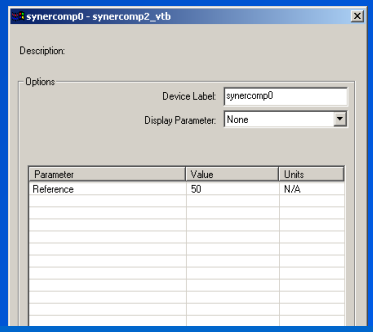


2) Specify signal o
natural coupling









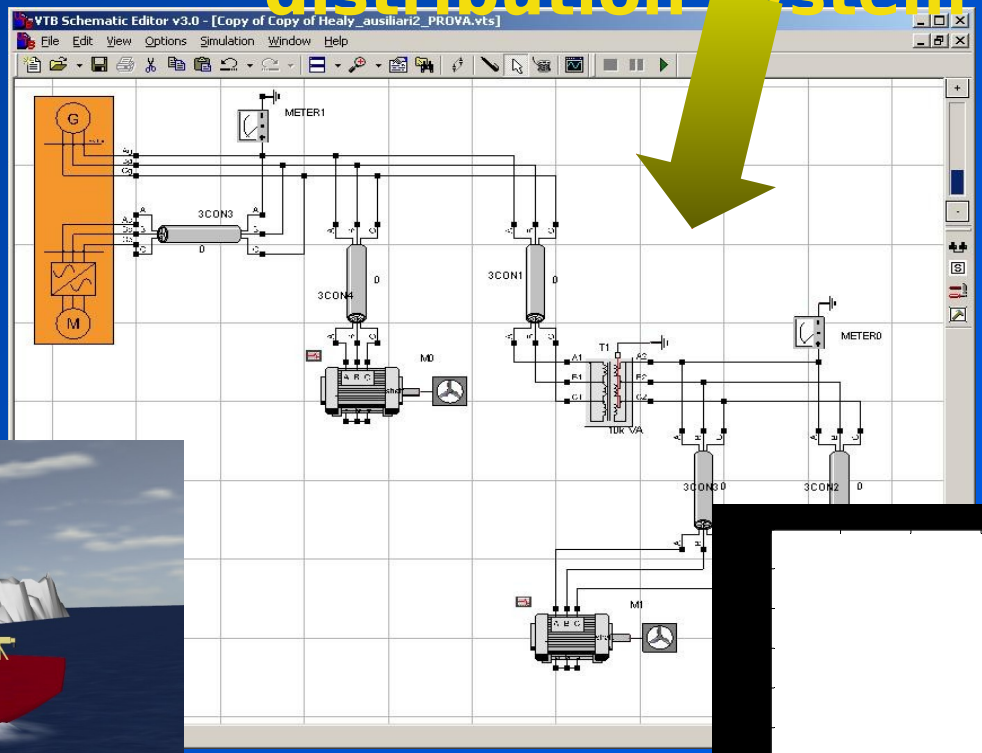
3) Select user-adjustable paramete

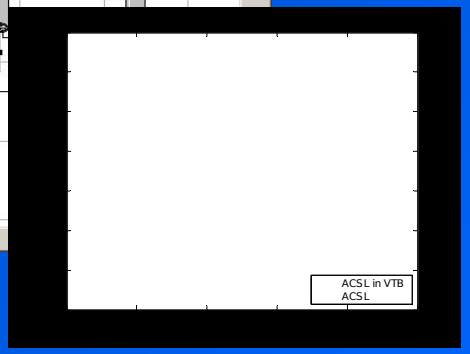
Wrapping and Iconizing of models adds new value to legacy models

Legacy model of electric plant
(from powering studie

ACSL code

New elaboration of the electric power distribution system





US Coast Guard Icebreaker “Healy”

VTB supports collaboration while protecting sensitive data

- VTB has demonstrated international distributed simulation – part of the system in Russia, part in US.
- There is no fundamental difference between component-based distributed simulation and hardware in the loop simulation
- Depending on channel bandwidth and latency, models or hardware can be located anywhere. Preserves proprietary or export-sensitive components or information while still allowing performance assessment at the system-level

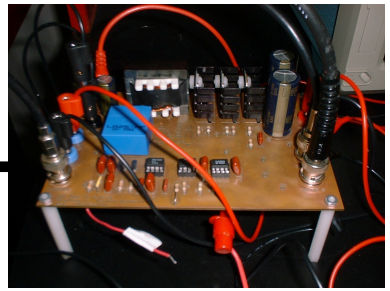
VTB Realtime runs under Linux RT, supports HIL

Linux RT

+

DAQ-I/O

+



Power Interface

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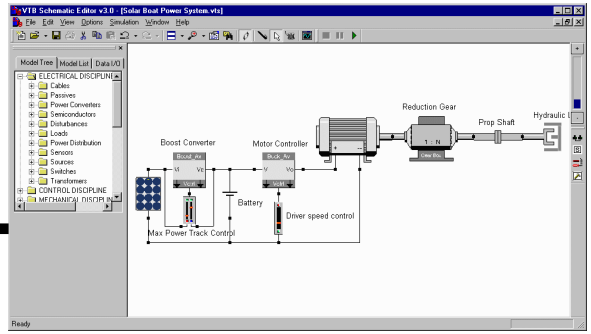

VTB RT

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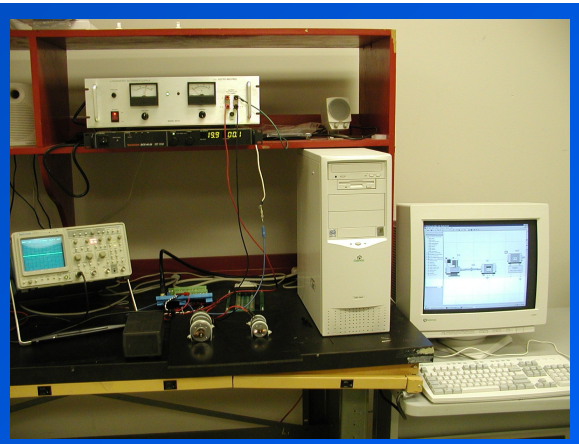
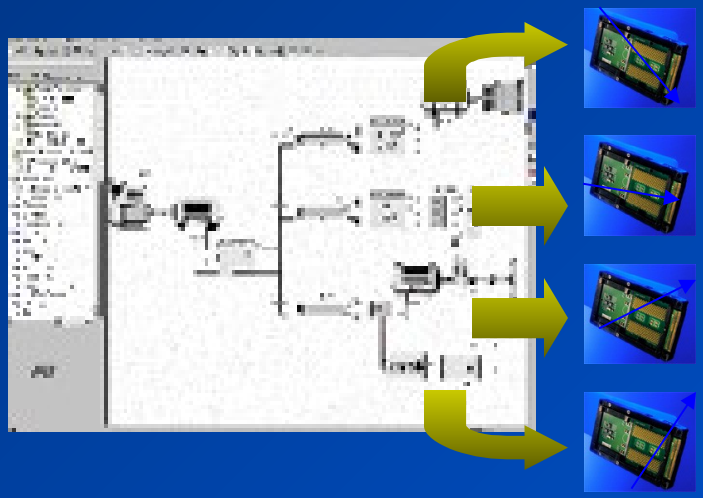


Realtime VTB on Itanium Multi-Processor system running Linux

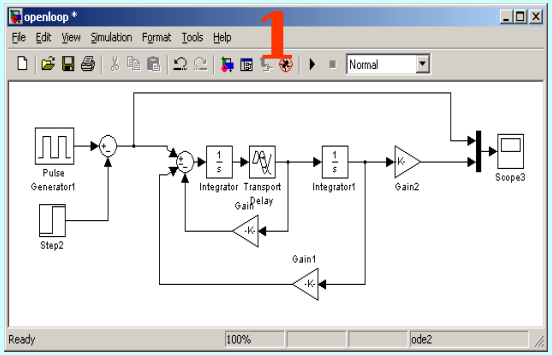
Adds multi-threaded, multi-processor capability to VTB



64 bit floating point performance and wide memory bandwidth for high-performance computing
Multi-threaded solver maximally uses the available computing hardware

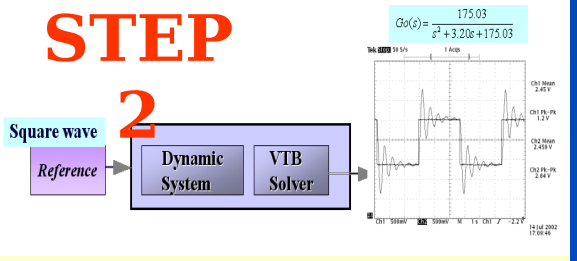
Realtime VTB with Hardware in the Loop

STEP 1



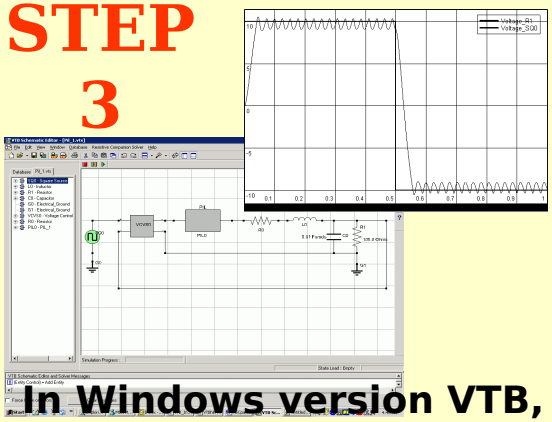
In Matlab/Simulink or Windows VTB, design the dynamic system and the controller

STEP 2



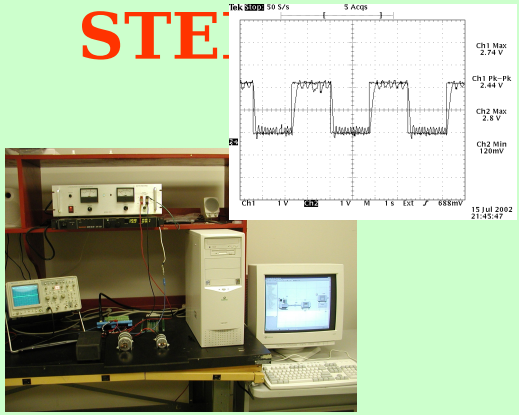
In RTVTB, perform open loop simulation to test real-time simulator

STEP 3



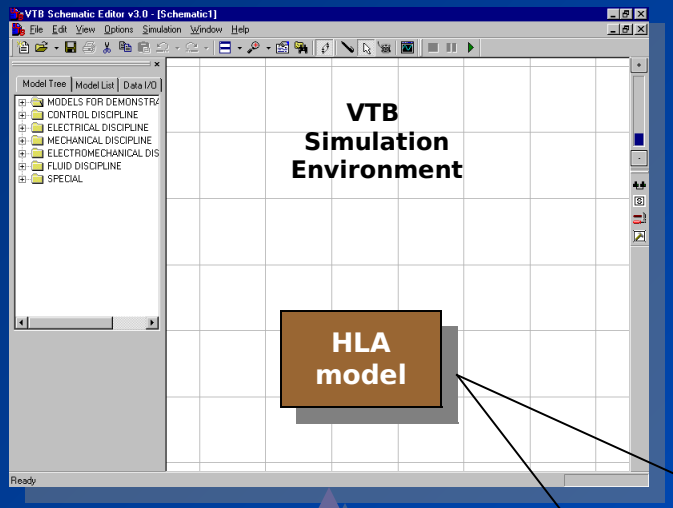
In Windows version VTB, perform closed-loop (Processor In the Loop) simulation to test the system hardware

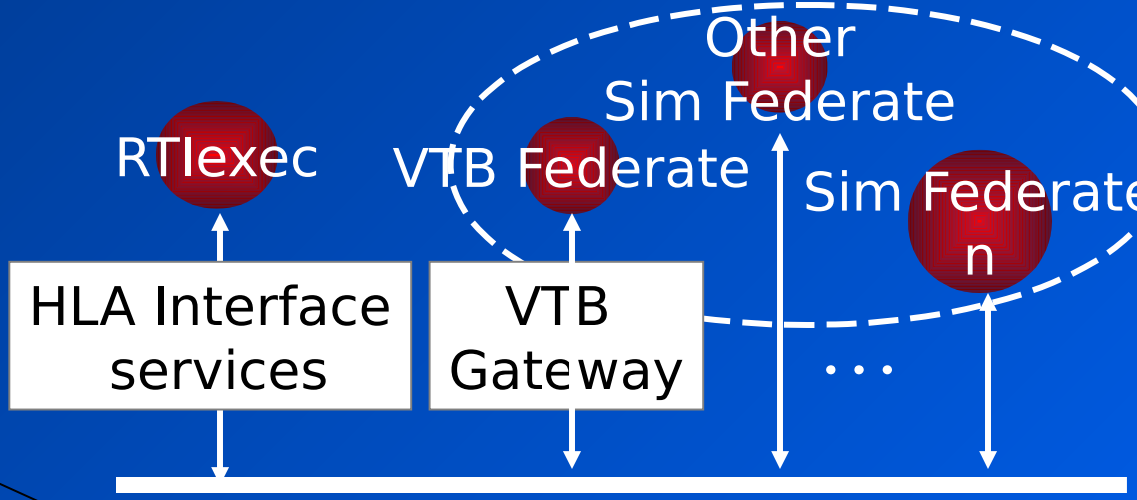
FINAL STE



In Linux version RTVTB, perform closed-loop (HIL) simulation

HLA compatibility



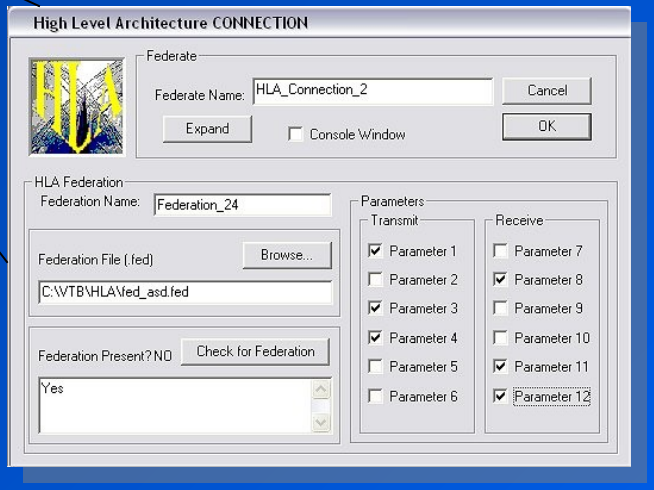


HLA Run-Time Infrastructure

Simulation Environment 1 — MacOS

Simulation Environment 2 — Windows

Simulation Environment 3 — Linux

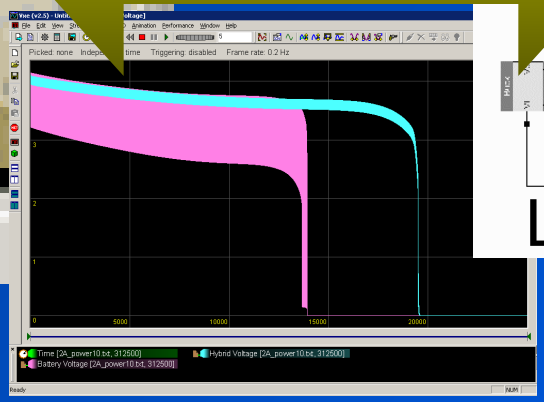


HLA capability allows VTB to support Dynamic Mission Planning

Land Warrior

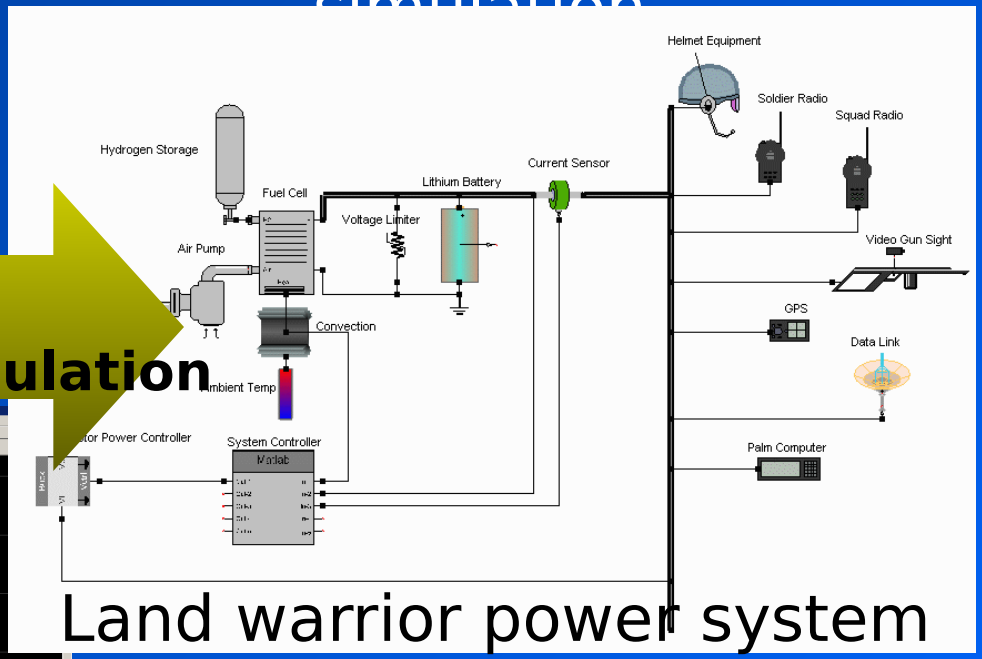
Distributed war game for soldier training and mission planning

HLA for Distributed Simulation



VTB

Power system simulation



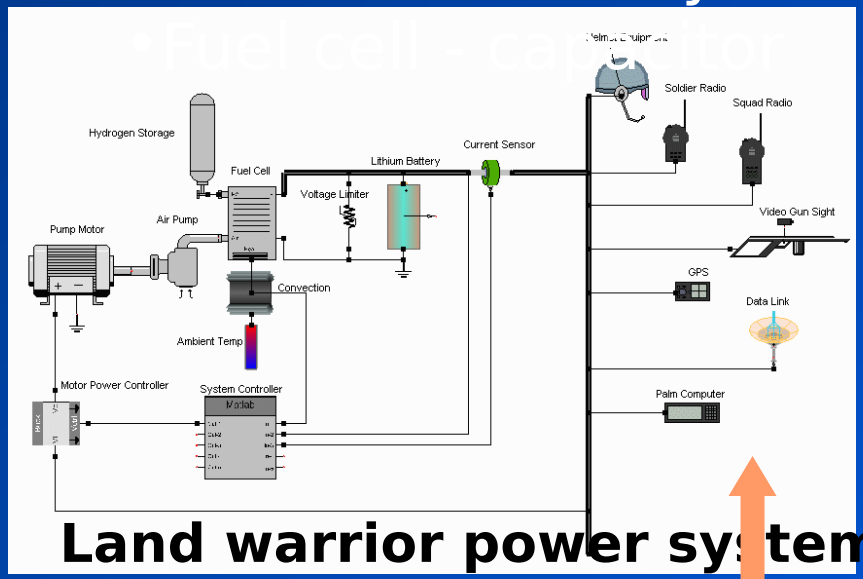
Land warrior power system

Test suitability of power source under mission conditions

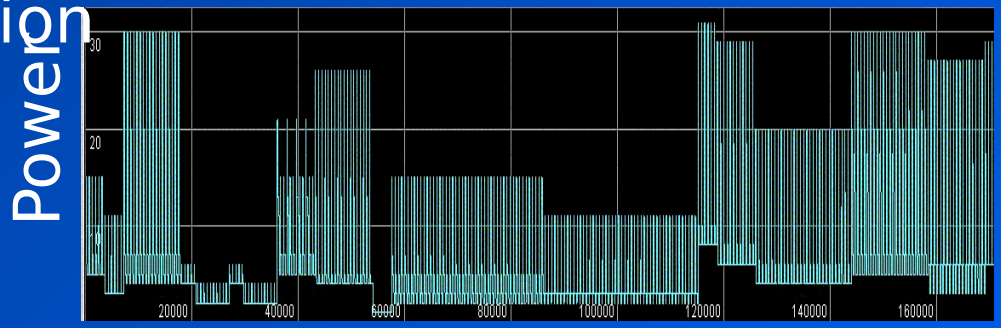
VTB supports system optimization in a mission-planning context

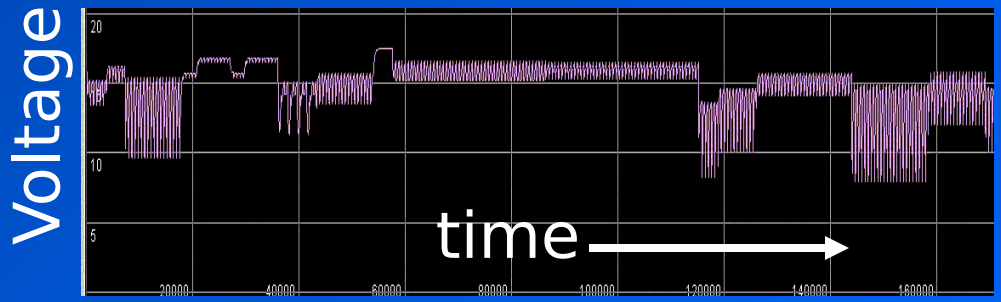
Simulation models are used to compare performance of two kinds of hybrid systems during a particular mission

- Fuel cell - battery
- Fuel cell - capacitor



Land warrior power system

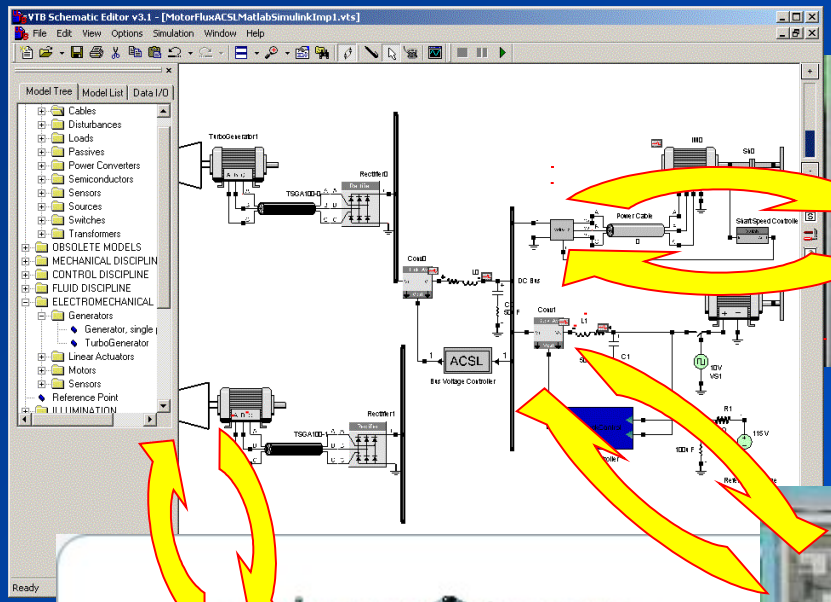


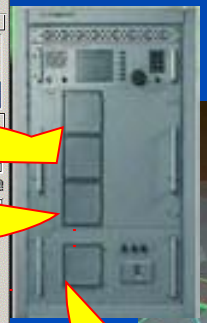


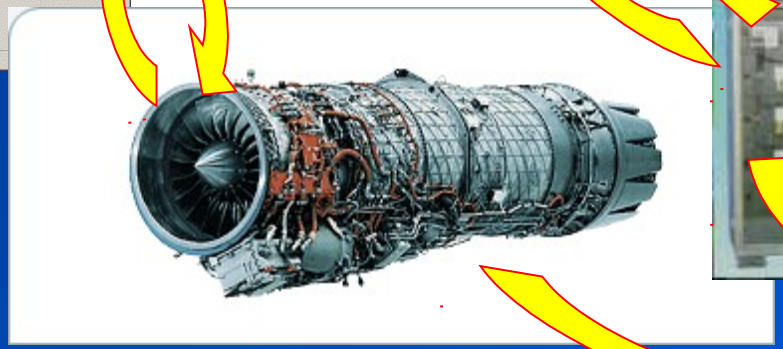
Mission profile for each equipment programmed using

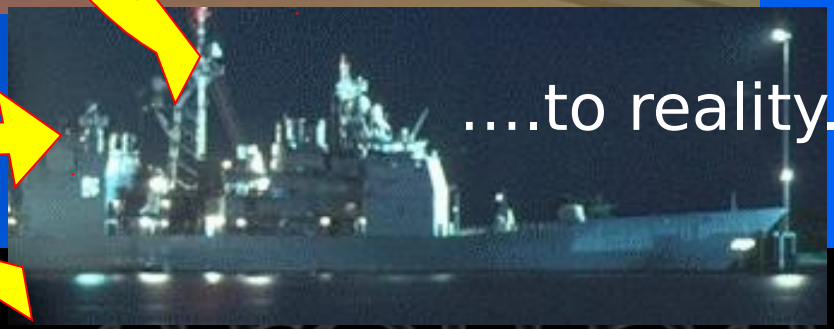
VTB blazes the pathway towards Incremental Virtual Prototyping

From concept...





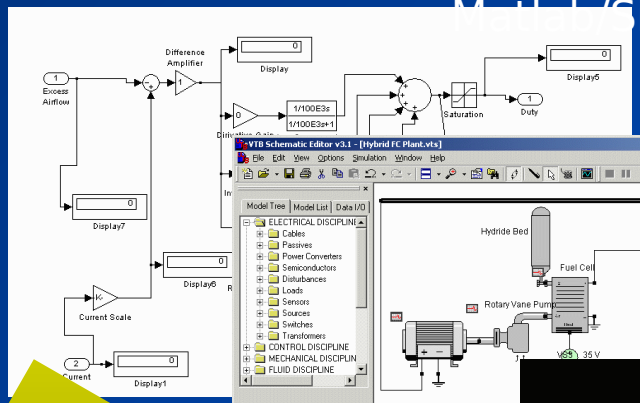




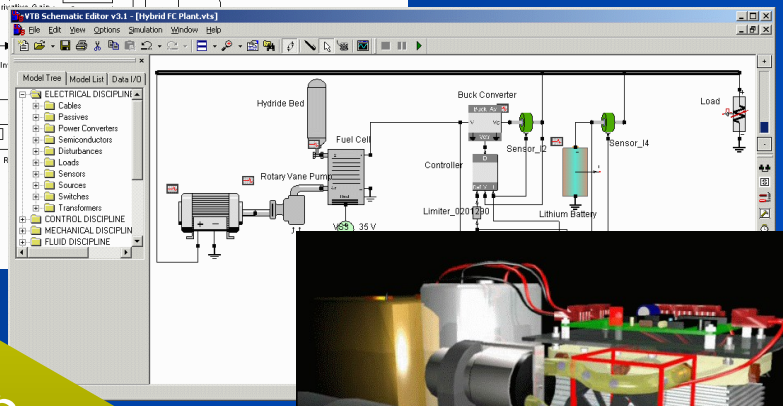
....to reality.

VTB provides a mature path for control development/insertion

Controllers are designed using Matlab/Simulink



The Simulink controller is dropped into VTB...



... then interactively tested and tuned using a high-accuracy system model

After compiling, the controller model can be distributed to any partner...

...who can test the power source to see how it will work with another load

.... or the controller can be loaded onto dSpace hardware

...to test a hardware prototype

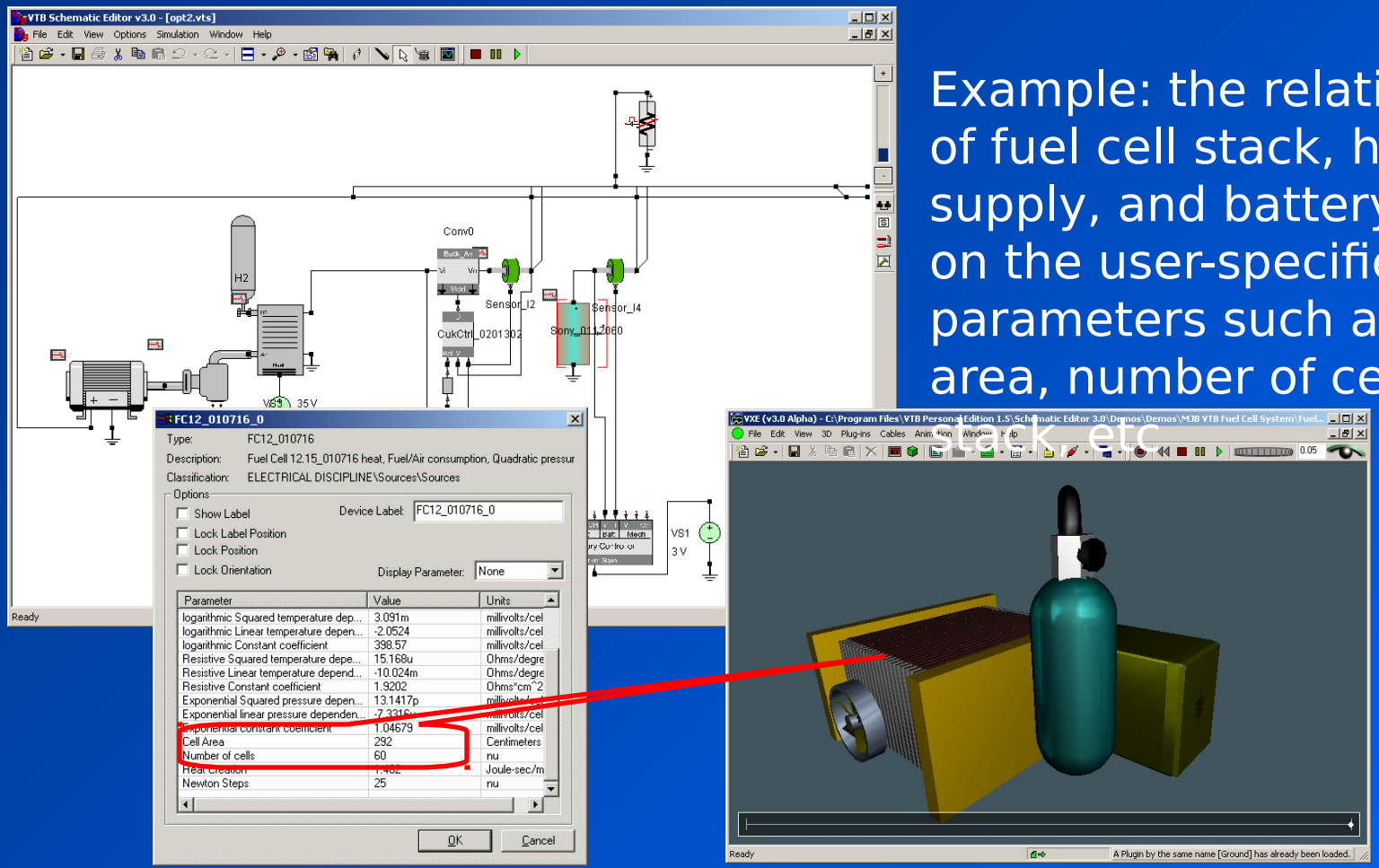
Finally test code on embedded processor that communicates with the simulation model

From concept to hardware

Processor-in-the-loop

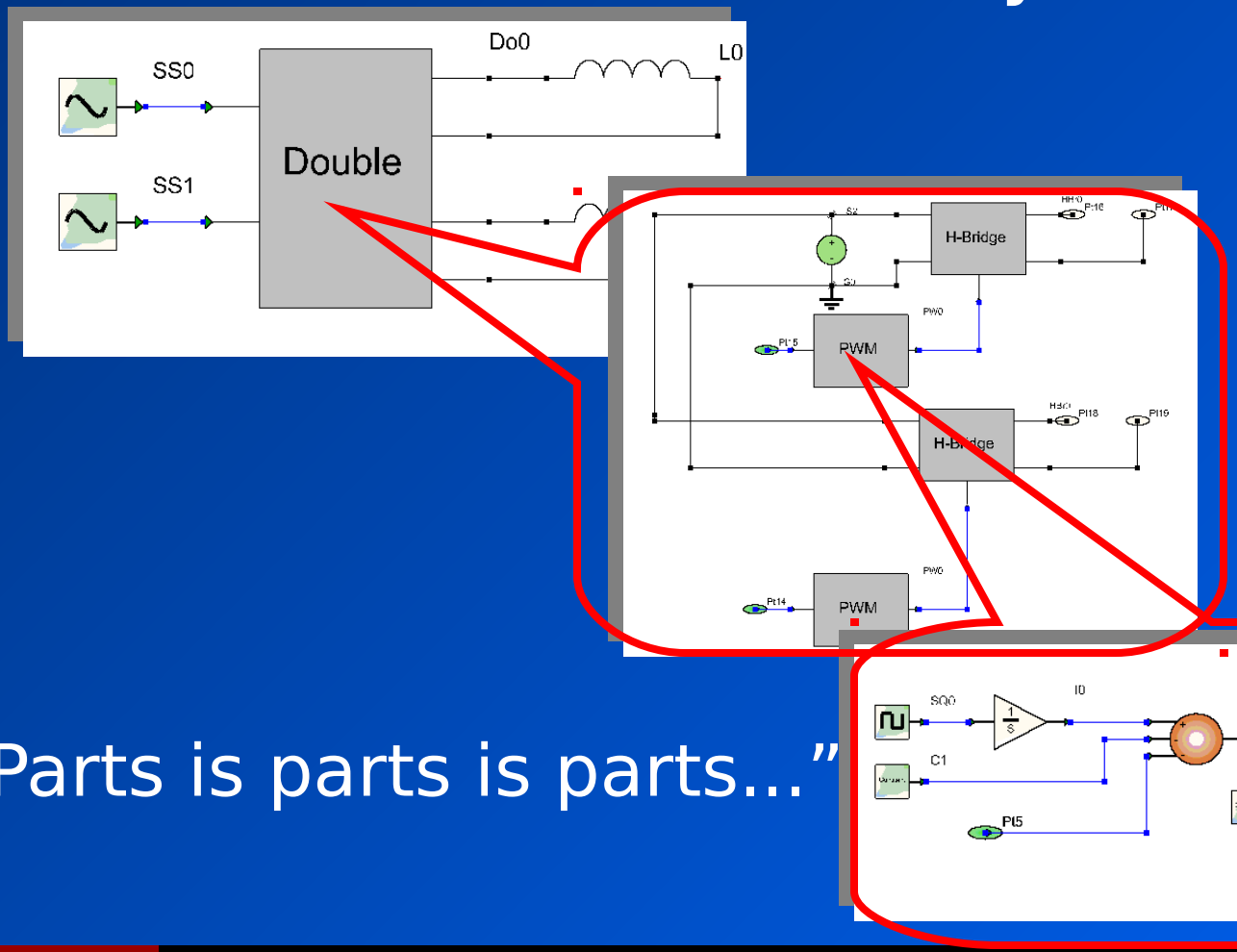
VTB Realtime supports realtime interaction with industrial controllers that are used in real systems. Allows testing of algorithms for embedded control in a risk-free environment

Visualizations aid understanding of system tradeoffs


VTB Schematic Editor v3.0 - [opt2.vts]
File Edit View Options Simulation Window Help
Conv0
H2
Sensor_I2
Sensor_I4
VS3 35 V
VS1 3 V
Ready
FC12_010716_0
Type: FC12_010716
Description: Fuel Cell 12.15_010716 heat, Fuel/Air consumption, Quadratic pressur
Classification: ELECTRICAL DISCIPLINE\Sources\Sources
Options
Show Label
Lock Label Position
Lock Position
Lock Orientation
Device Label: FC12_010716_0
Display Parameter: None
Parameter | Value | Units
logarithmic Squared temperature dep... | 3.091m | millivolts/cel
logarithmic Linear temperature depen... | -2.0524 | millivolts/cel
logarithmic Constant coefficient | 398.57 | millivolts/cel
Resistive Squared temperature depe... | 15.168u | Ohms/degre
Resistive Linear temperature depend... | -10.024m | Ohms/degre
Resistive Constant coefficient | 1.9202 | Ohms*cm^2
Exponential Squared pressure depen... | 13.1417p | millivolts/cel
Exponential linear pressure dependen... | -7.3316 | millivolts/cel
Exponential constant coefficient | 1.04679 | millivolts/cel
Cell Area | 292 | Centimeters
Number of cells | 60 | nu
Heat Creation | 1.402 | Joule-sec/m
Newton Steps | 25 | nu
OK
Cancel
VXE (v3.0 Alpha) - C:\Program Files\VTB Personal Edition 1.5\Schematic Editor 3.0\Demos\Demos\MJB VTB Fuel Cell System\Fuel...
File Edit View 3D Plug-ins Cables
Ready
A Plugin by the same name [Ground] has already been loaded.

Example: the relative sizes of fuel cell stack, hydrogen supply, and battery depend on the user-specified parameters such as cell area, number of cells in stack, etc

New capability for hierarchical definition of systems



Any subsystem can be represented by a user-defined icon

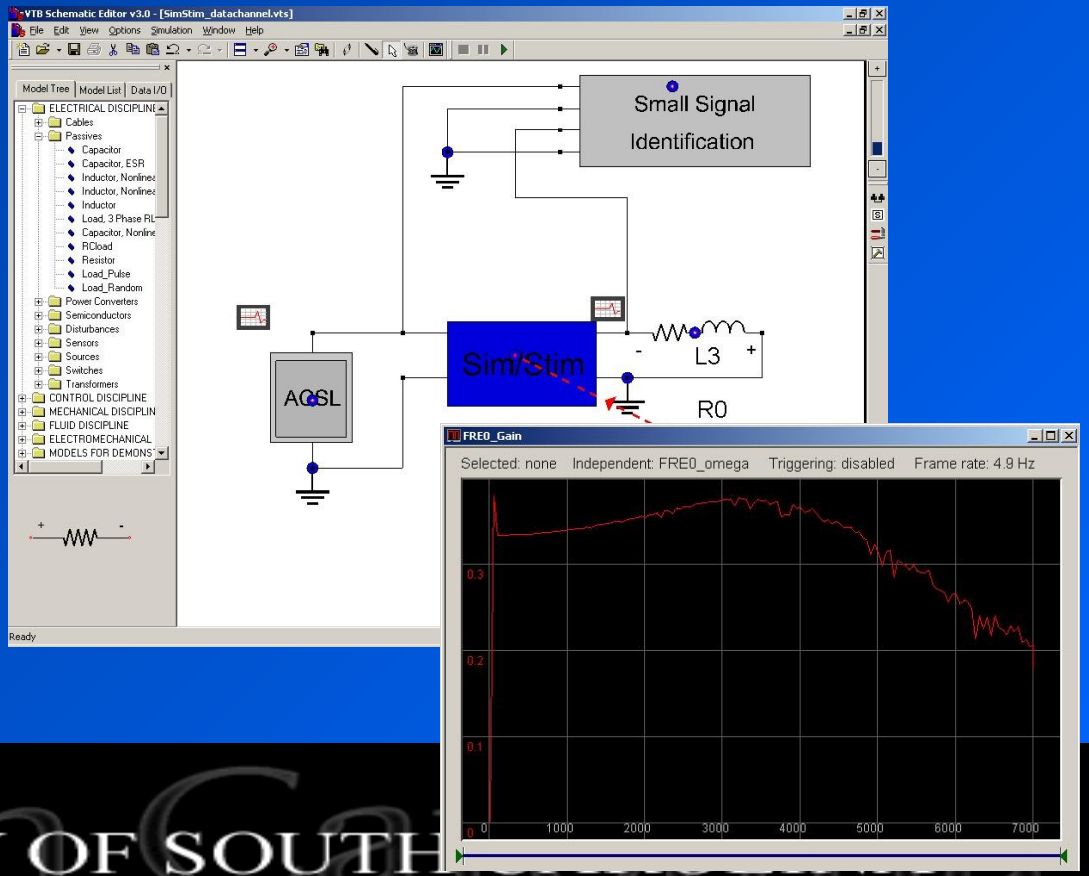
"Parts is parts is parts..."

System Analysis Tools

- Consider VTB as a virtual Hardware Testbed
- Any diagnostic that can be run on real hardware can be run on the virtual system
- Tools for frequency domain analysis probe the system in the time domain, as one would do with real hardware

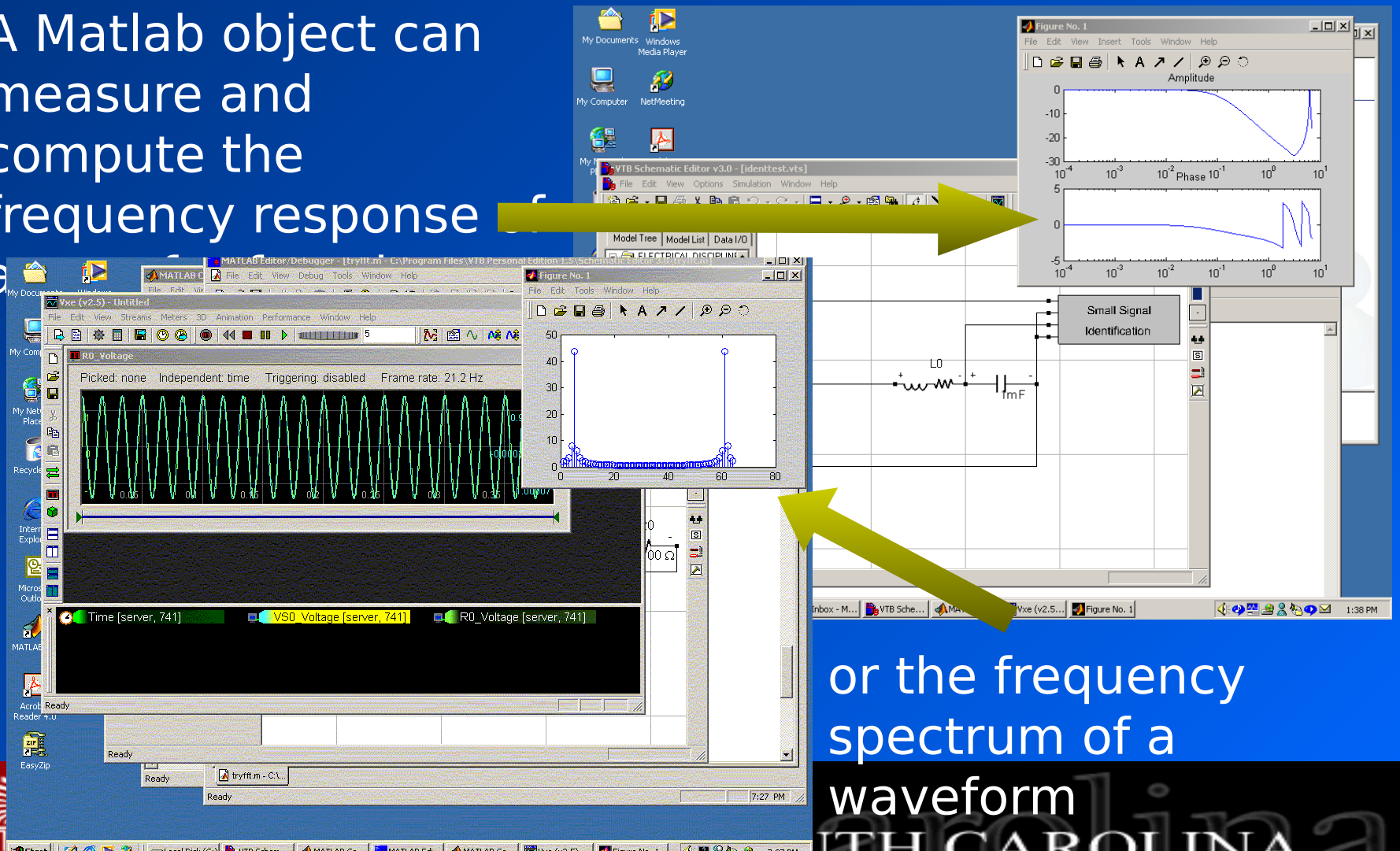
New System Analysis Tools

- Use established tools such as Matlab System Identification toolbox to “experimentally” characterize frequency domain response
- Better than a real prototype – can “measure” unmeasurable properties
- Fast wavelet based analysis tools for interactive or real time system identification



Small Sig Freq Analysis

A Matlab object can measure and compute the frequency response a



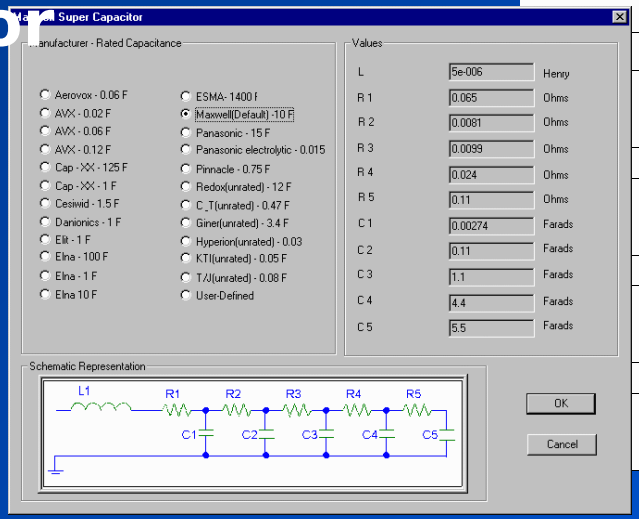
or the frequency spectrum of a waveform

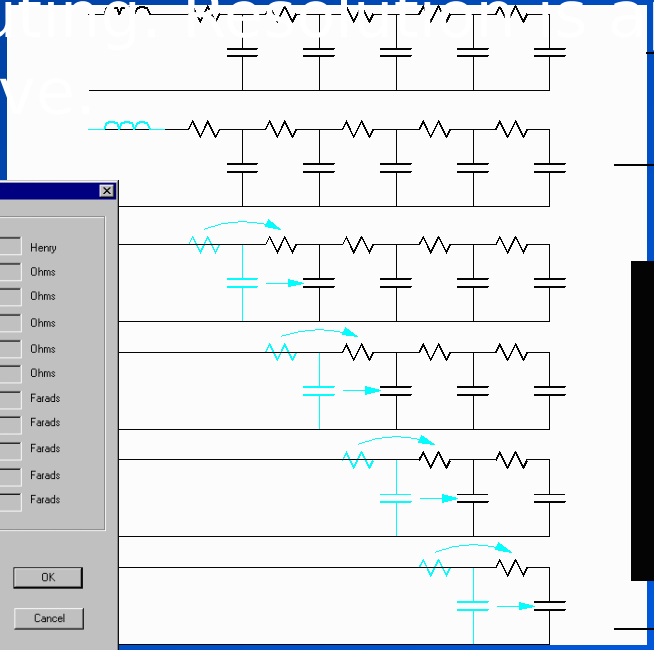
UTH CAROLINA

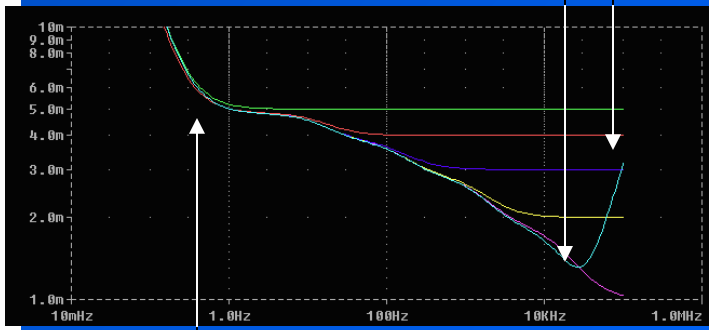
Models can have multiple levels of detail

- Different studies require different levels of model detail
- VTB allows automatic model order reduction to speed computing. Resolution is appropriate to the study objectives.

Supercapacit
or

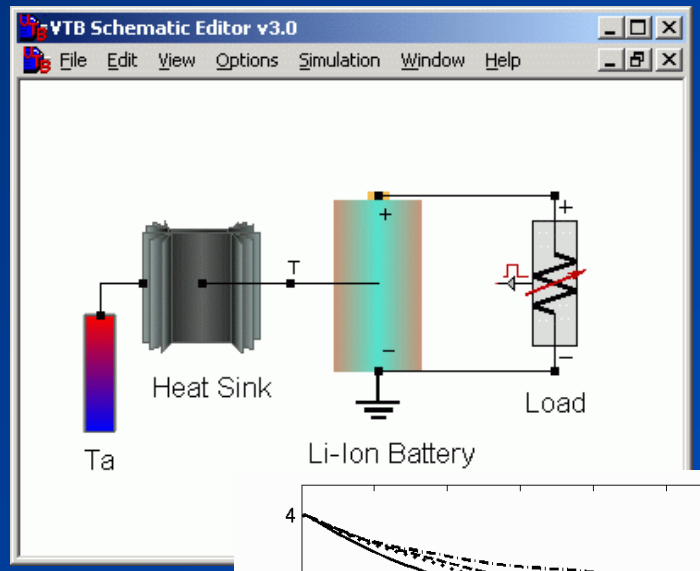


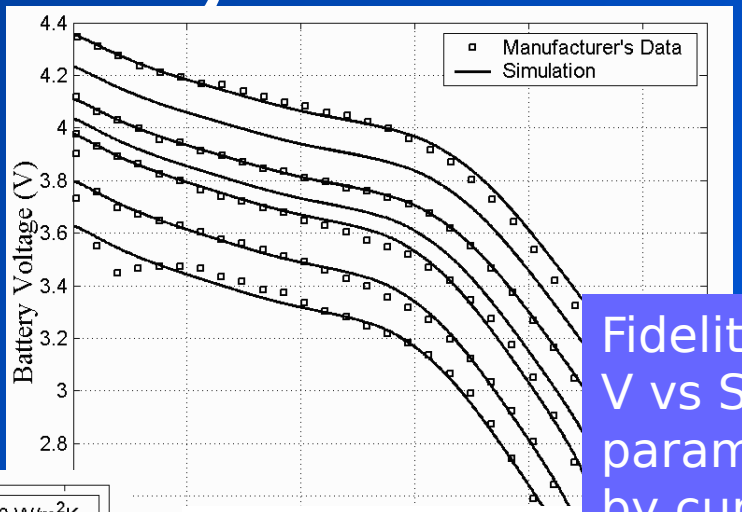




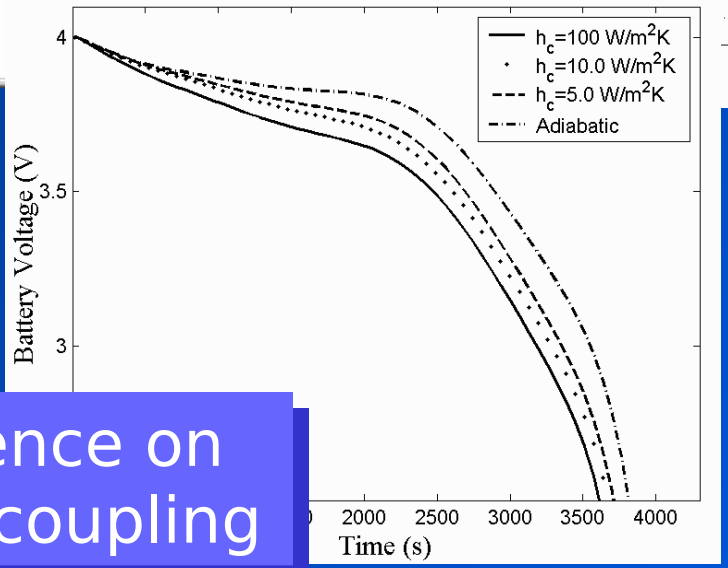
Frequency responses

Lithium Battery Models

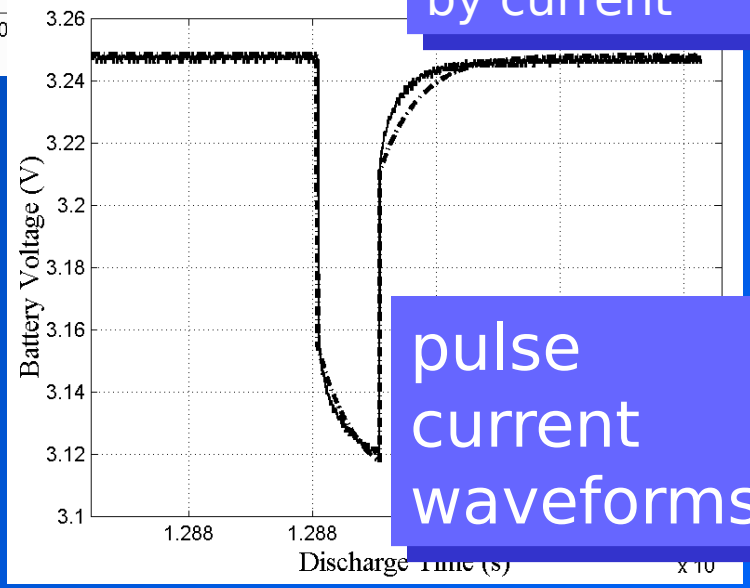




Fidelity of V vs SOC parameterized by current

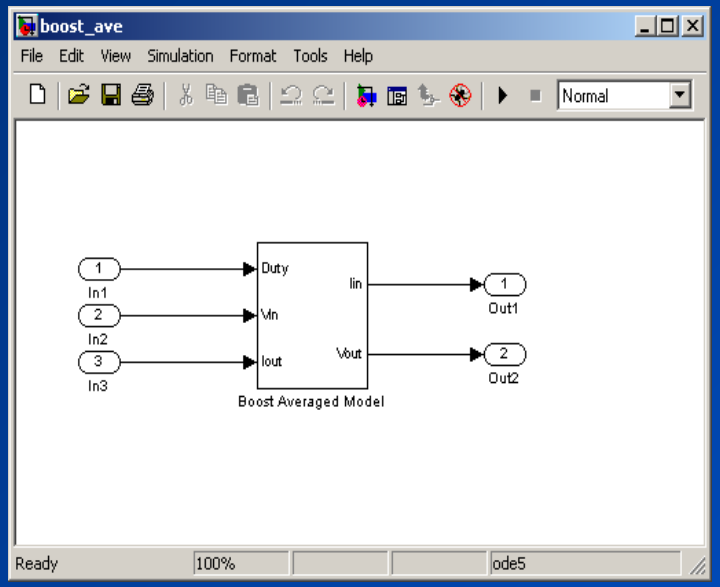


Dependence on thermal coupling



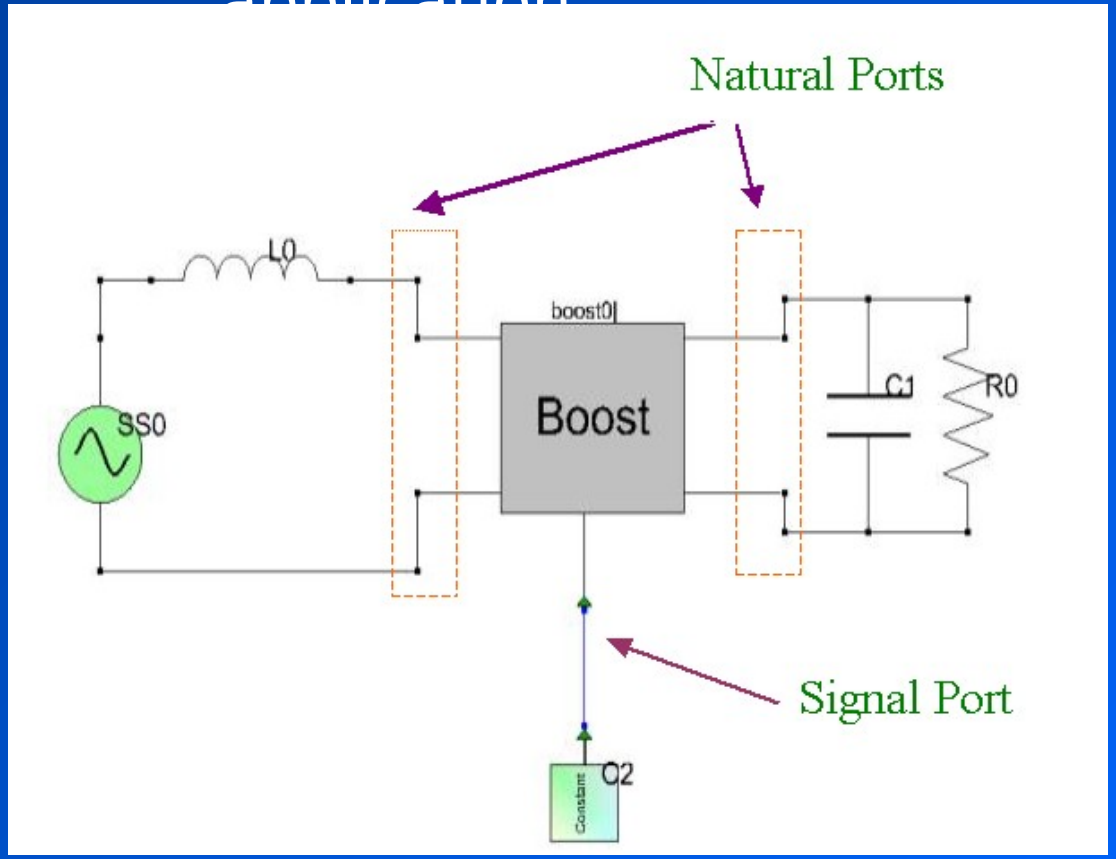
pulse current waveforms

Simulink model in VTB



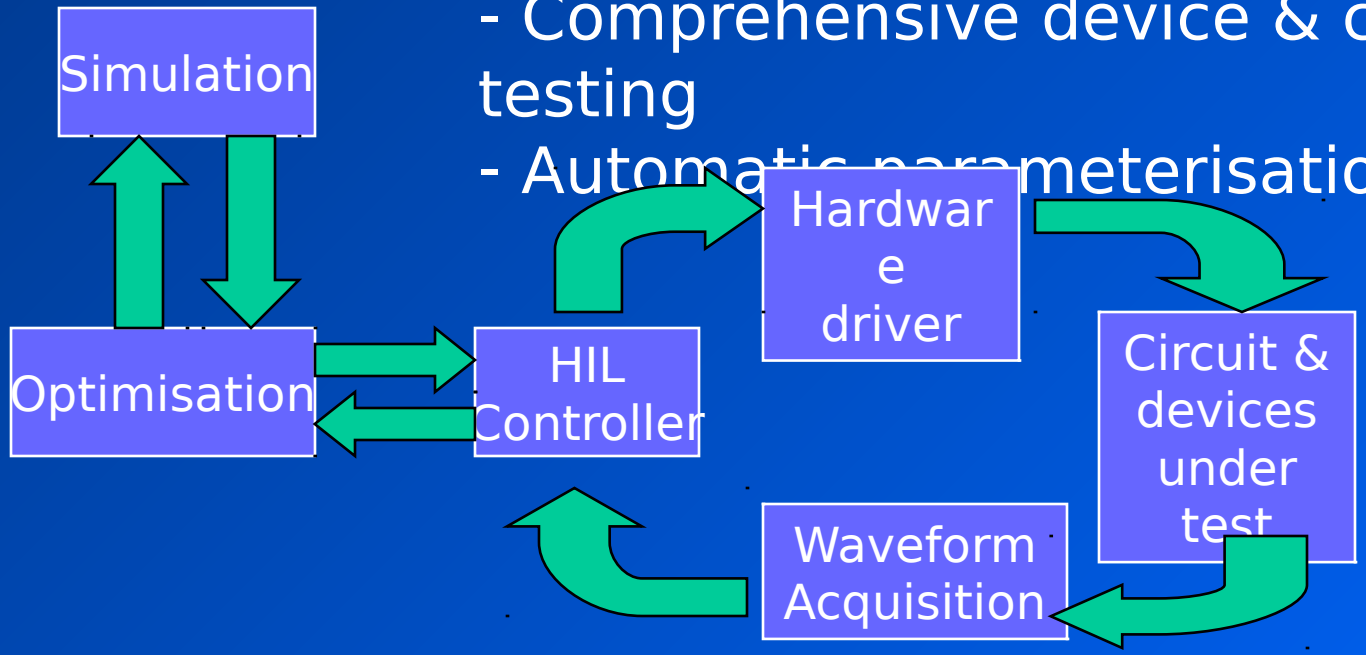
Simulink Schematic of boost converter

VTB Schematic of boost converter application

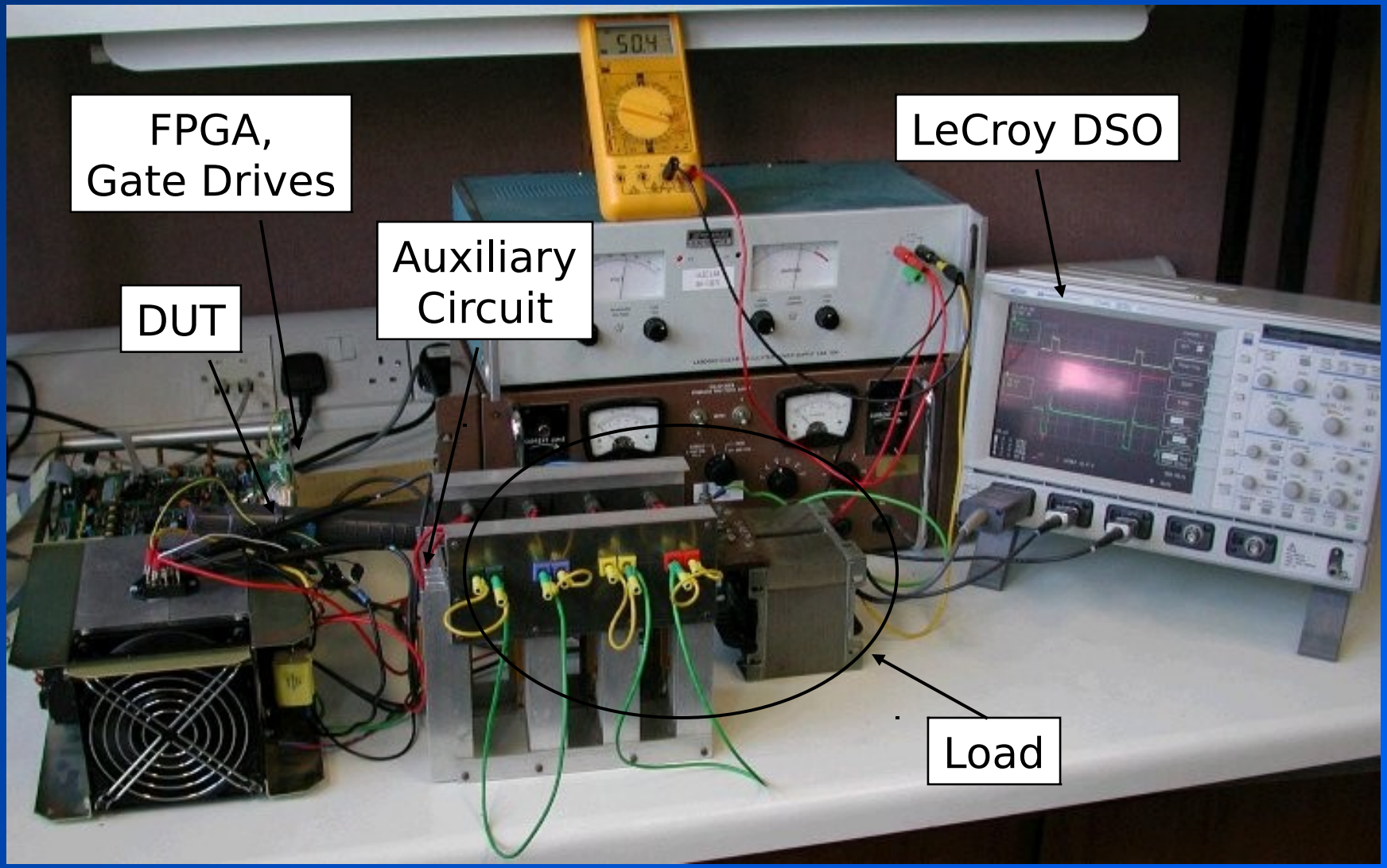


Hardware-in-the-Loop for System Optimization

- Range of conditions applied
- Linked to simulation & optimisation
- Applications:
  - Comprehensive device & circuit testing
  - Automatic parameterisation



Experimental Setup



Just to wake you up….

New Labview Interface Validates Test Automation

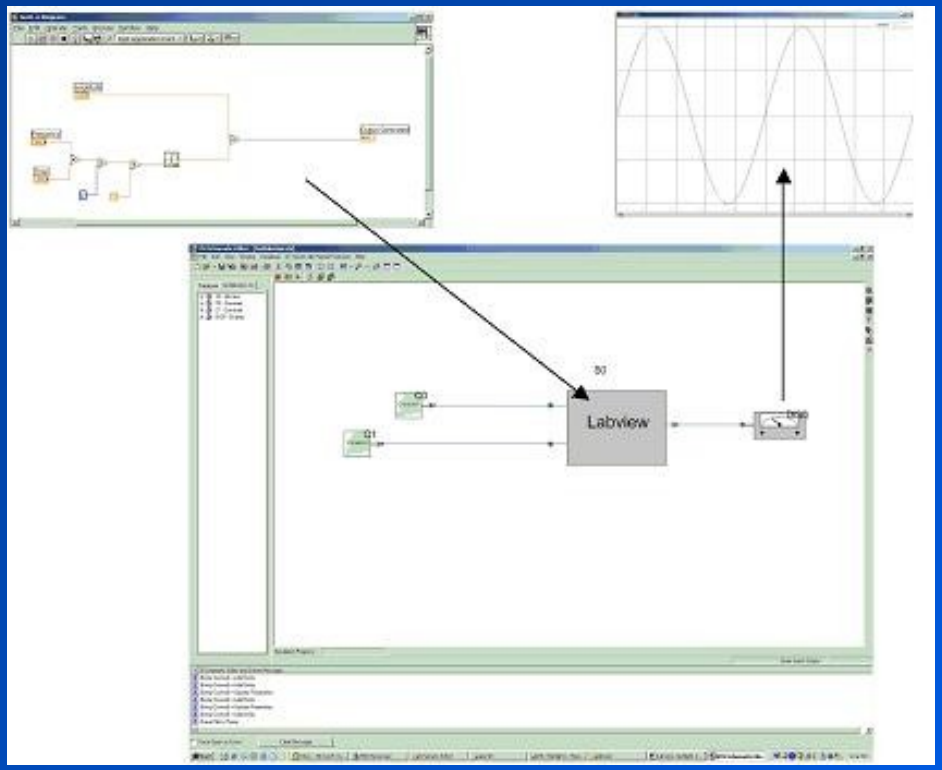
- New interface to LabView allows representation of the “plant” in VTB.
- Then LabView data acquisition and control can be tested in the synthetic plant before deployment in critical applications where errors could be costly

VTB-LabView co-simulation

- LabView Virtual Instruments (VIs) are widely used for measurement, monitoring and control. Advanced AI tools are available.
- Extreme and/or pathological system conditions can be safely produced within the virtual environment of VTB, which then safely supports...
- ...Design, testing, and training of VIs for complex systems

VTB-LabView co-simulation

LabView exports the VI as a .dll

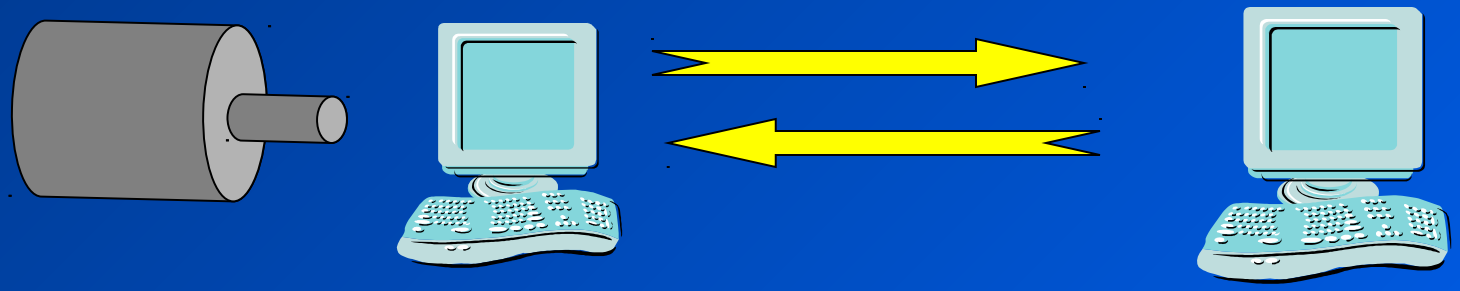


The Labview VI is inserted into a system defined within the VTB Schematic Editor

As the simulation runs, the VI block executes acquiring data from the system simulated in VTB

VTB-Labview link supports remote testing

- Allows testing of complex systems before all components are physically assembled at one site
- Demonstration example: remote testing of an inverter-fed induction motor



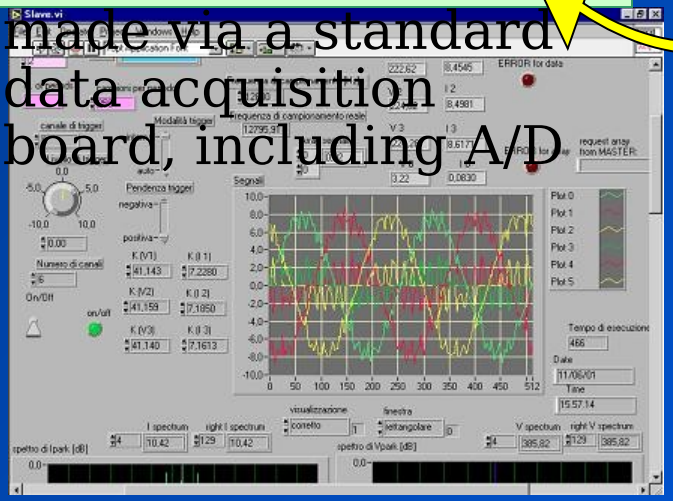
Inverter-fed induction motor
Sensors
LabView RDA Server
Location: Polytechnic Univ of Milan, Italy

VI executed within VTB
Visualization of acquired data
Location: USC, USA

Test of the Virtual Environment

Politechnic de Milano

- Has real operating drive
- Measurements are made via a standard data acquisition board, including A/D

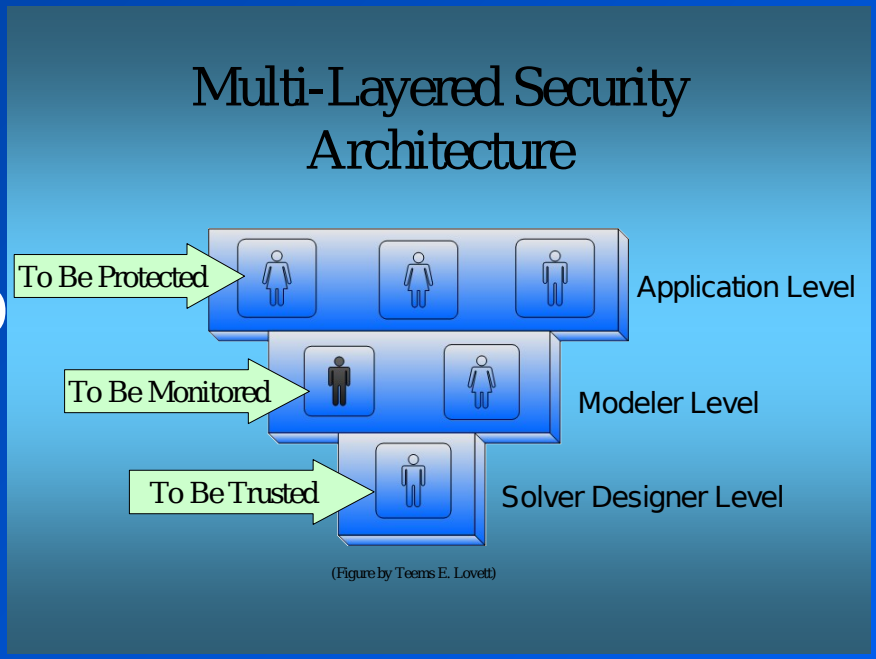


USC

- Simulates in VTB a 3.5 kW induction motor fed by a six-step inverter
- Labview VI executes within VTB environment, acquiring three-phase currents and voltages
- Labview VI also acquires real measurements through access to the LabView RDA Server in Italy
- Waveforms of real/virtual equipment can be compared

New Initiative in VTB Security

- Malicious models?
- Network security
- Simulation sandbo



Implementation methods

- **Static Method** (Before Execution)
  - VTB model source code analysis
  - Compiled VTB Model code analysis
    - **Advantage: No overhead**
    - Disadvantage: Minimal protection against logic bomb
- **Dynamic Method** (During Execution)
  - Controlled execution (sandbox)
  - Pretest execution in simulate environment
    - **Advantage : High level protection**
    - **Disadvantage : Resource competitions**

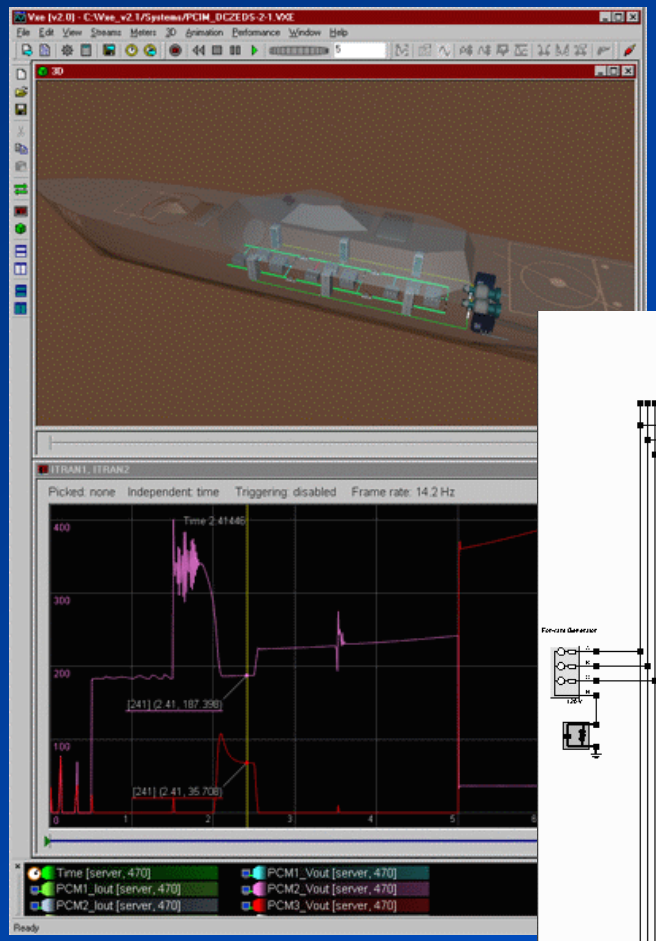
VTB moves to support simulation under uncertainty

- Important in top-down design
- Uncertain specifications or performance characteristics
- Partial model data
- Uncertain model parameters
- Empty or partial models

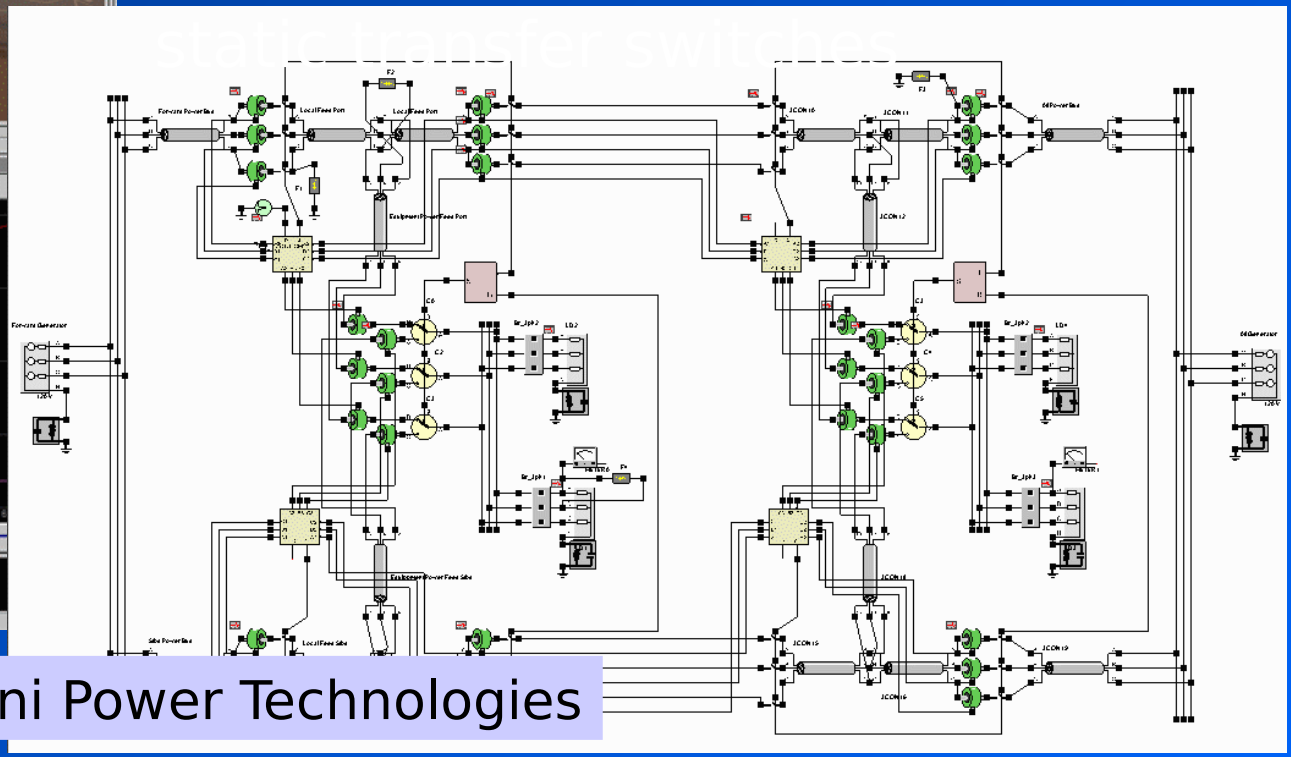
VTB Group research in Advanced Electric Power Systems

- AEPS Goals:
  - Develop models of reference systems
  - Study dynamic performance of advanced electric power systems
  - Develop tools for characterization of (virtual) systems
  - Perform architecture trade-off studies

Survivable AC Zonal Systems


Picked: none Independent: time Triggering: disabled Frame rate: 14.2 Hz
Time [server, 470]
PCM1_Iout [server, 470]
PCM2_Iout [server, 470]
PCM1_Vout [server, 470]
PCM2_Vout [server, 470]
PCM3_Vout [server, 470]

Active current monitoring allows robust AC zonal power system with sub-transient switching of electronic circuit breakers and static transfer switches*



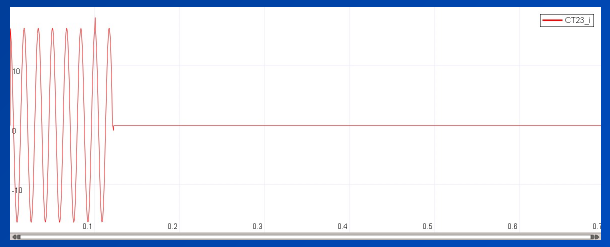
* Research with Omni Power Technologies

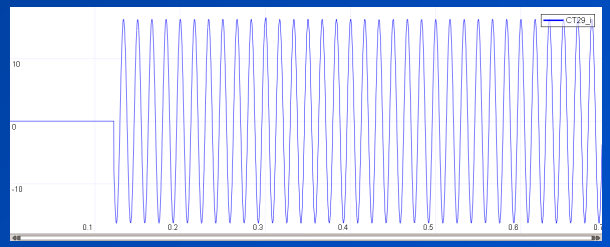
Provides Uninterrupted Power

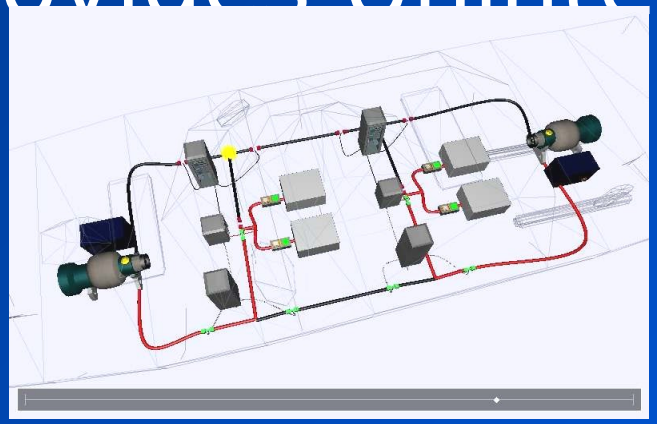
Feeder Cables Currents

Zone 1

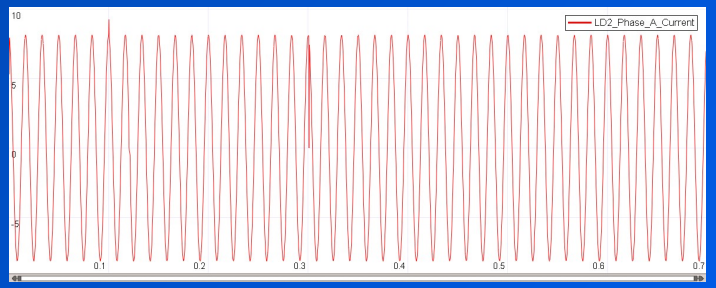
Zone 2

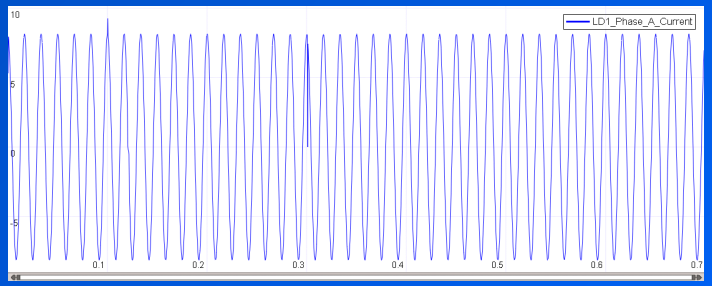






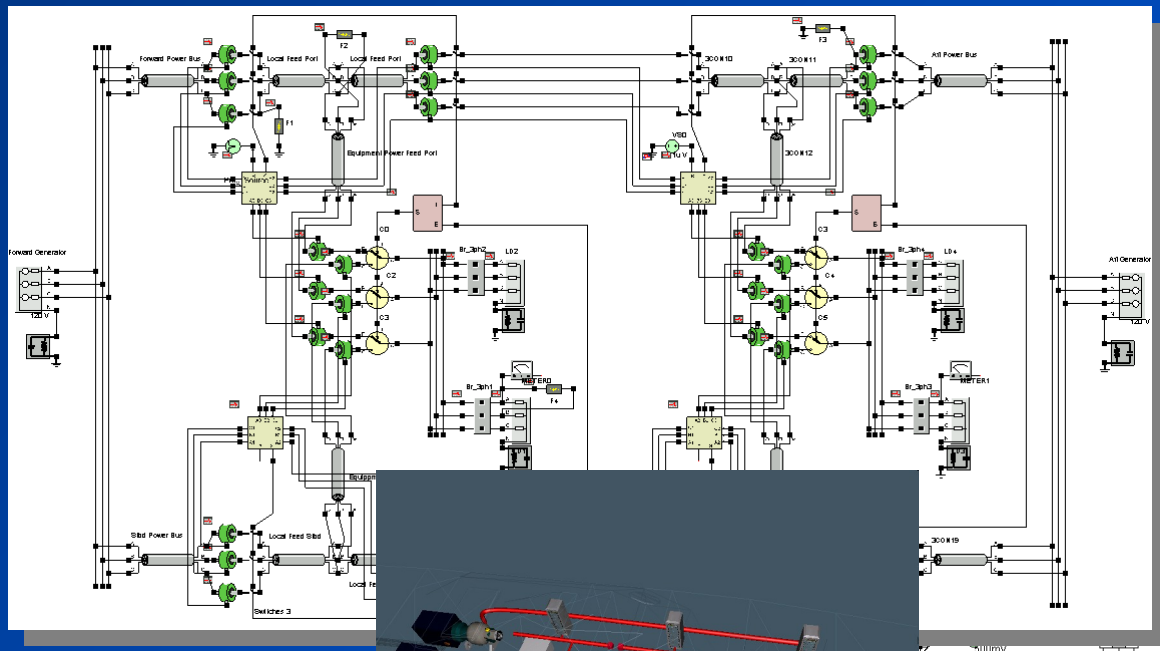
Load Currents



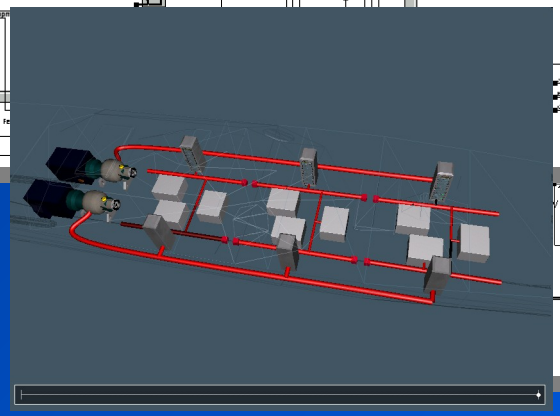


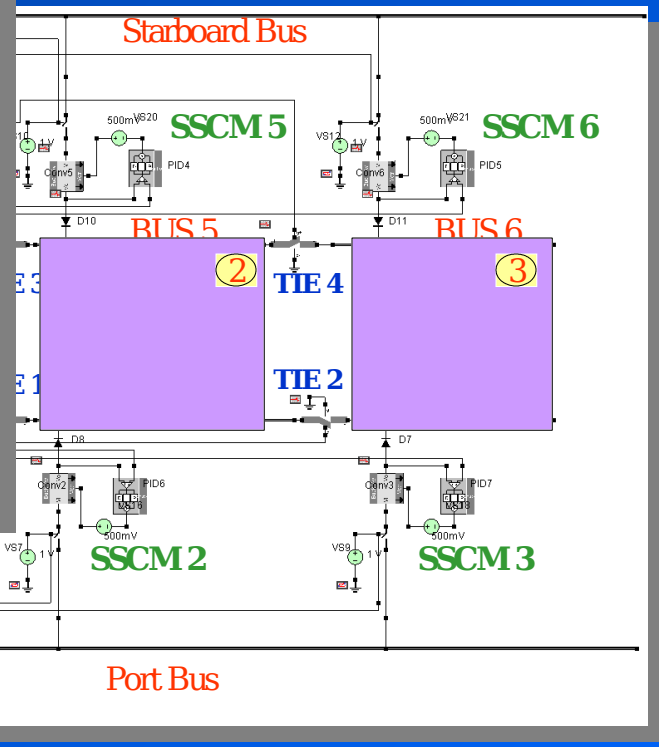
Developing Models of reference systems

AC zonal power system



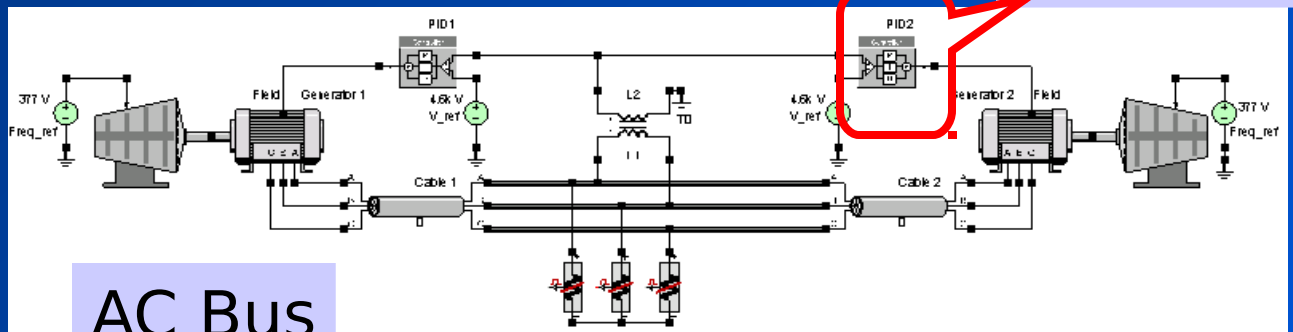
DC zonal power syste





Compare transient energy storage in Synchronous vs Asynchronous Power Sources (60 Hz vs DC distribution)

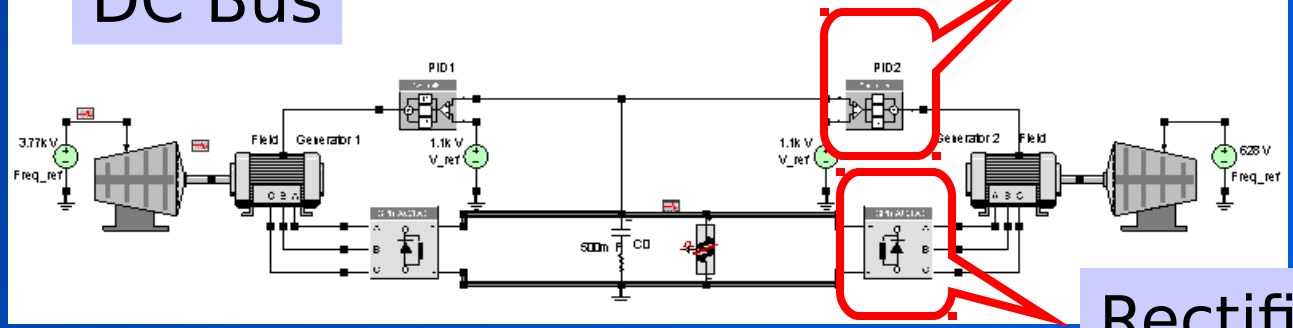
Bus voltage regulat



AC Bus

DC Bus

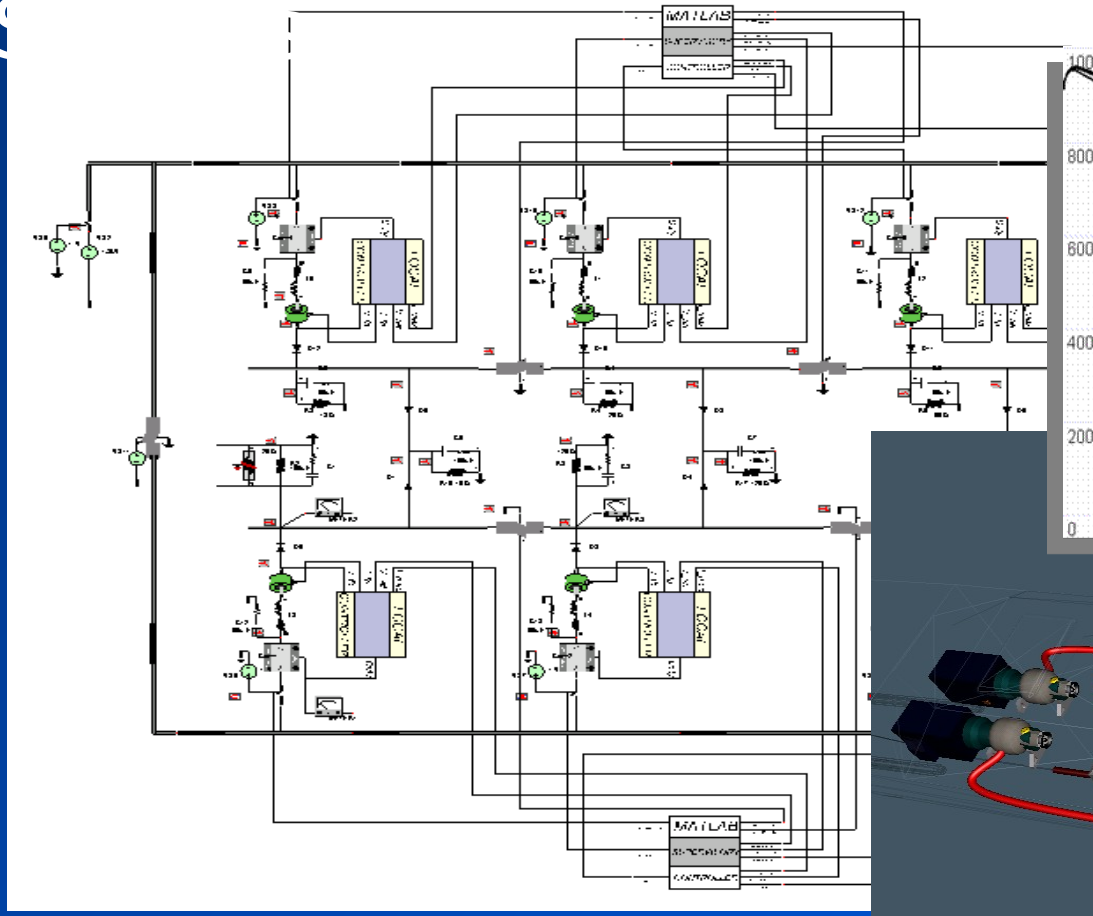
Bus voltage regulator

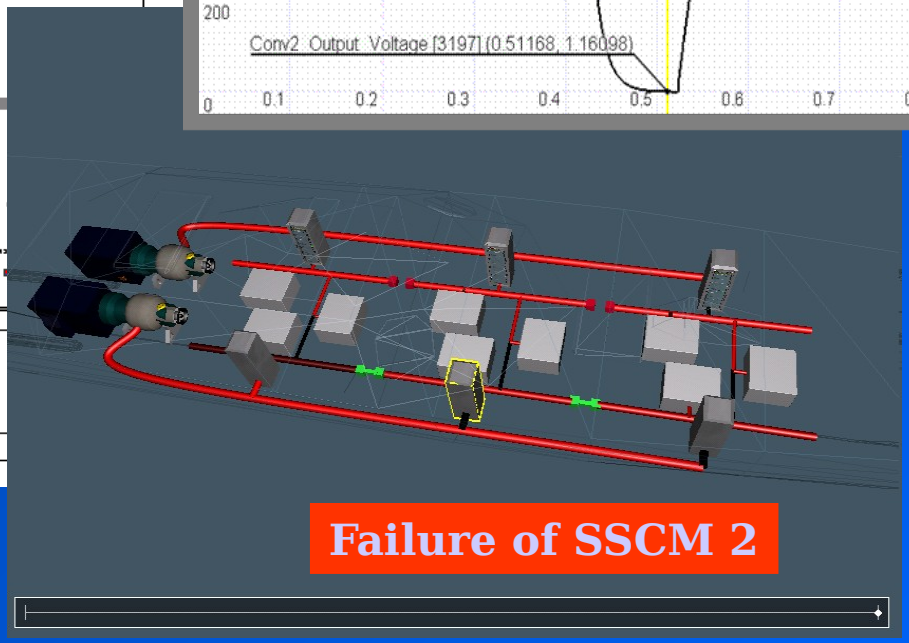


Rectifier

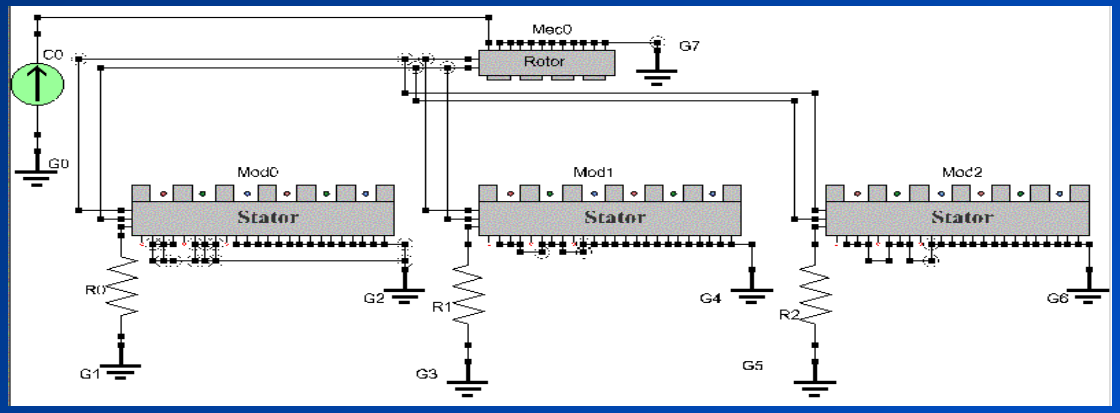
Since non-synchronous, more kinetic energy is available for support of large transients on the bus

DC Zonal Power System

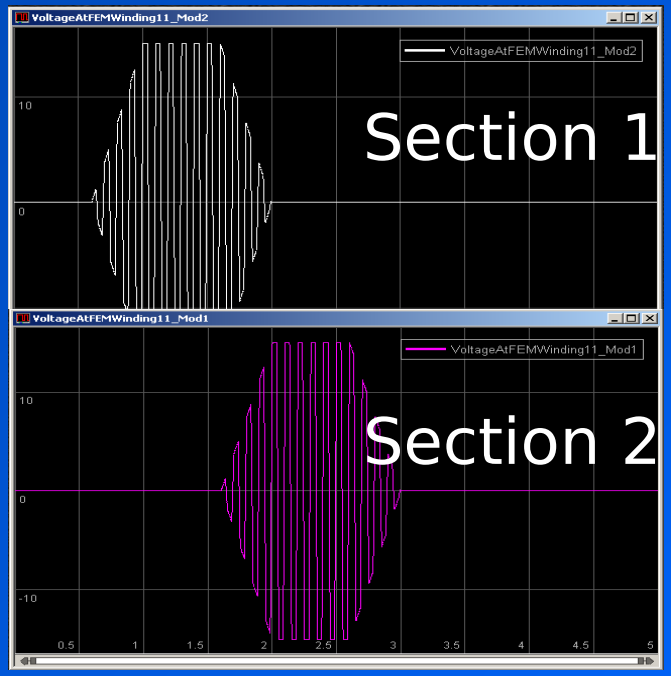




EMALS MODELING



Slider - Force elements of each section are summed to find speed and position EMF is returned to stator sections



Stator - Represents the current in a single winding and defines the force contribution of that stage to overall system force

Model Validation Test

System Characterization Tools

- 3 phase port impedance probe in DQ coordinates to assess stability
- Virtual destructive testing
  - Wavelet based methods for fault identification
  - Training of neural networks for fault identification in synthetic environment

Architecture Tradeoffs

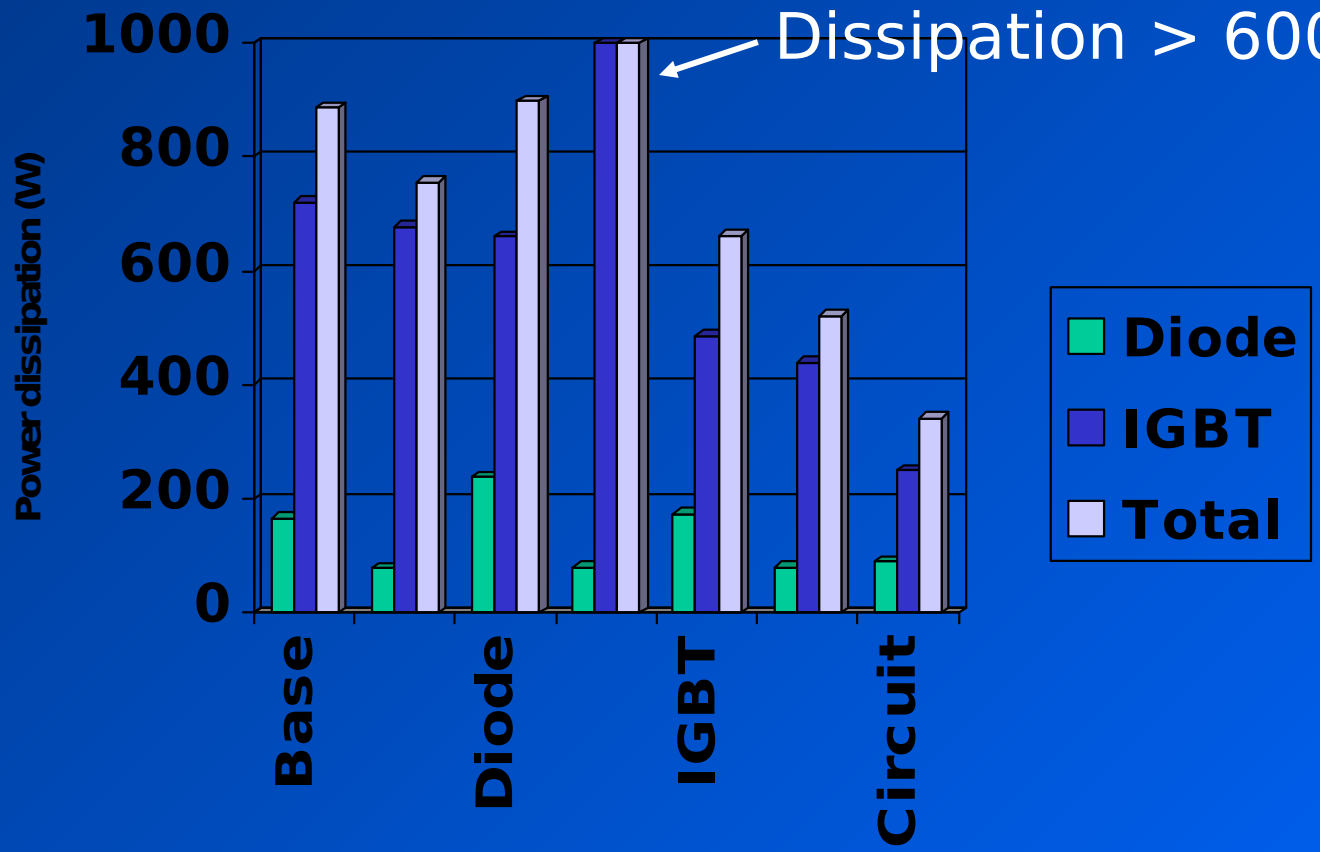
- Optimum location of DC link
  - Rectify one place, distribute DC
  - Distribute AC, rectify many places
- Accessibility and effectiveness of energy storage on the DC link and

Optimization of Power Modules

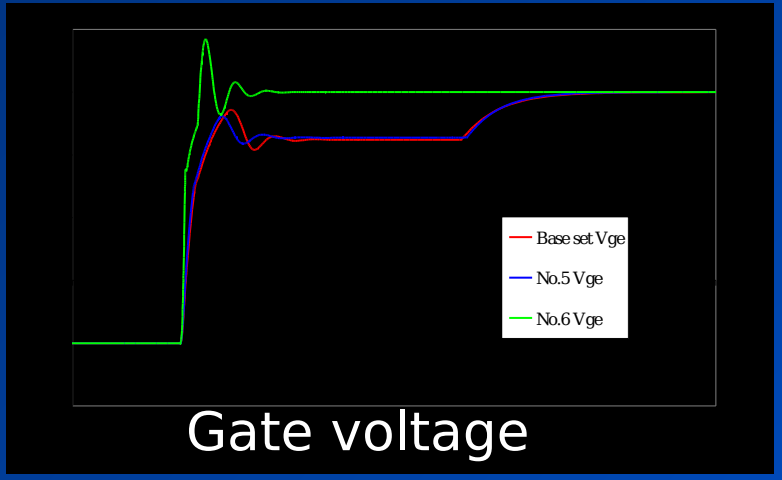
- Focus on optimization of the package as a whole, rather than just single components in the package
- Example - power switch and diode combination

Optimisation Results

- Diode and IGBT optimised individually and together
- Circuit optimised separately



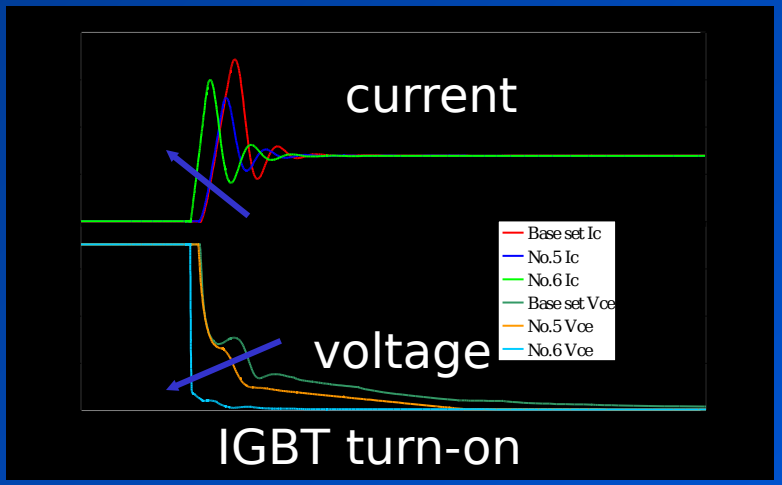
Switching Performance of Optimized Package during Turn-On



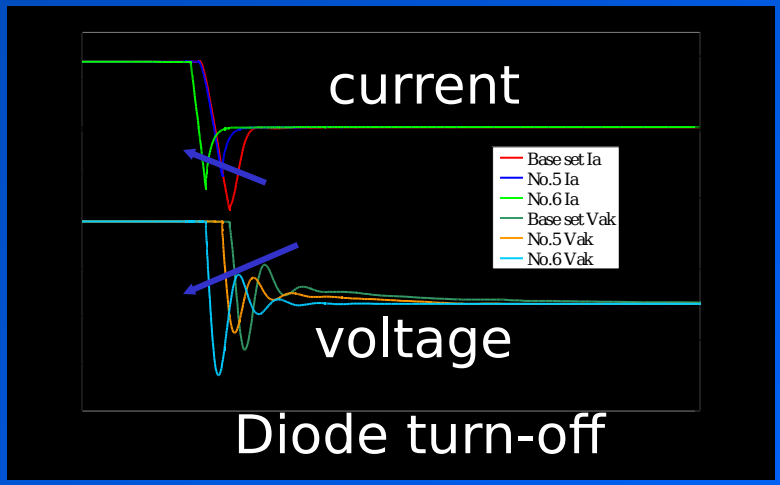
Gate voltage

- Diode recovery improved
- IGBT voltage tail reduced
- Similar results found during IGBT turn-off, diode turn-on

Base
IGBT and diode: A, W_B, N_B, τ (based on total power)
Circuit: R_G, L_S (based on total power)



IGBT turn-on

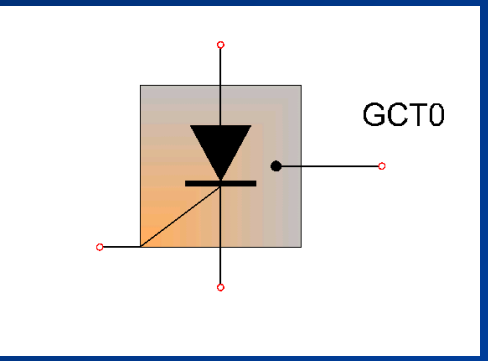


Diode turn-off

Power Device Modeling

Characterize, Model, and Simulate Power Devices at Temperatures from -150 to +150 ^{o}C

- Developed Parameter Extraction Algorithms for
  - IGBTs
  - Diodes
- Developed Electro-thermal Models of IGBTs, including
  - Punch Through
  - Non-Punch Through,
  - High Voltage,
  - Planar-Gate, and
  - Trench-Gate
- Developed Electro-thermal Model of Power Diode

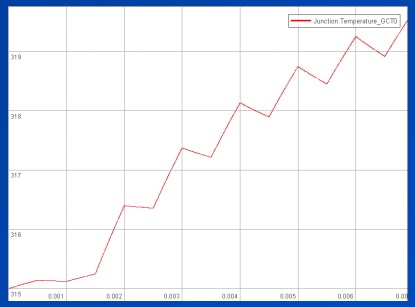


Example: Level-1 Model of IGCT
(Integrated Gate Controlled Thyristor)

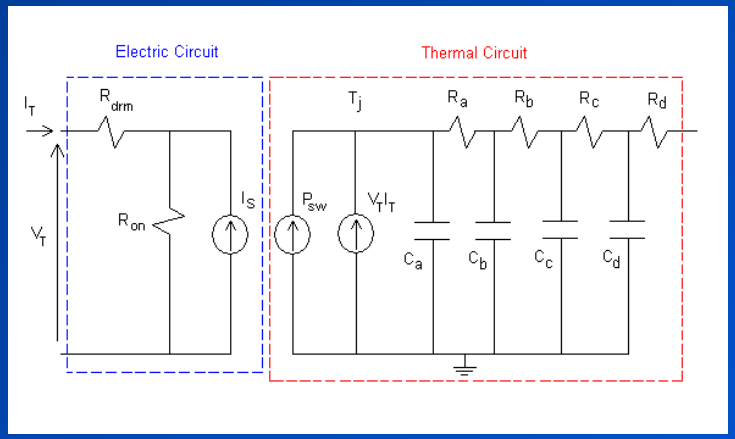
- V_{DRM} = 4500 V (repetitive peak off-state voltage)
- I_{TAVM} = 1700 A (maximum average on-state current; half sine wave)
- I_{TRMS} = 2700 A (maximum rms on-state current)

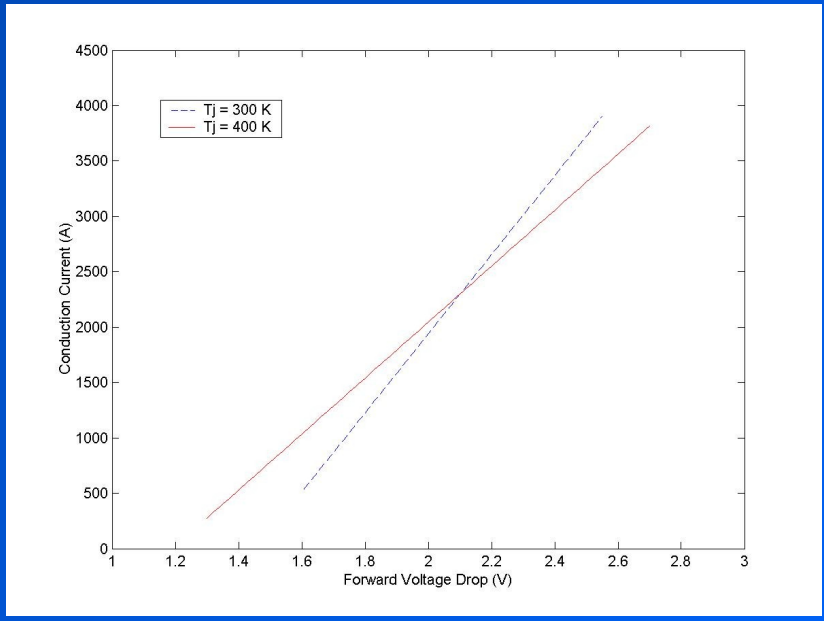
$$E_{sw\_on} = \frac{V_T}{6} t_r$$

$$E_{sw\_off} = m_E I_T$$

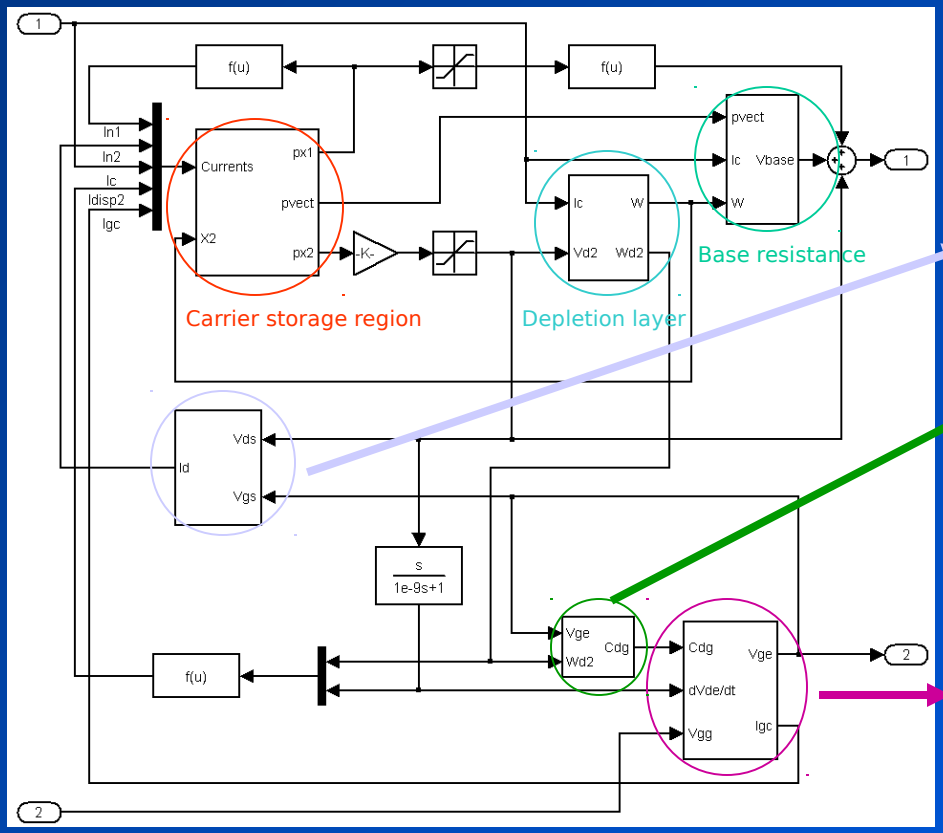


$$I_T = 3.57 \times 10^3 \left[\frac{T_j}{300} \right]^{-1.2} \qquad V_T = 5.2 \times 10^3 \left[\frac{T_j}{300} \right]^{-1.9}$$

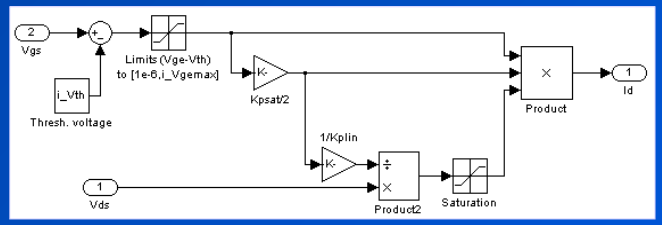




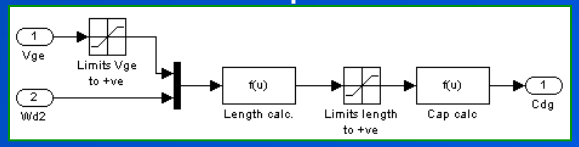
Level-3 Model of IGBT in MATLAB/SIMULINK



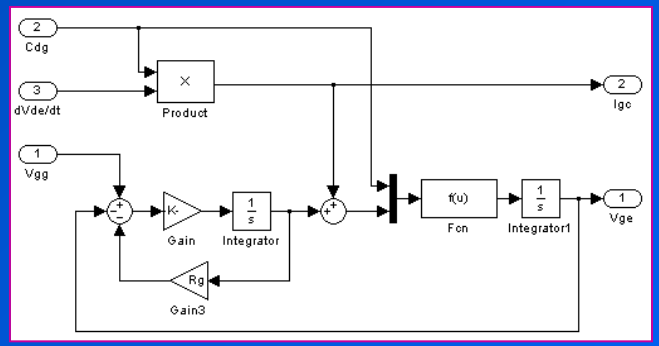
MOSFET conduction



Miller capacitance



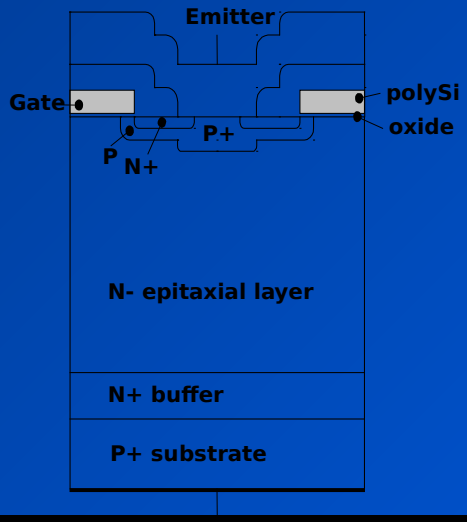
Gate circuit

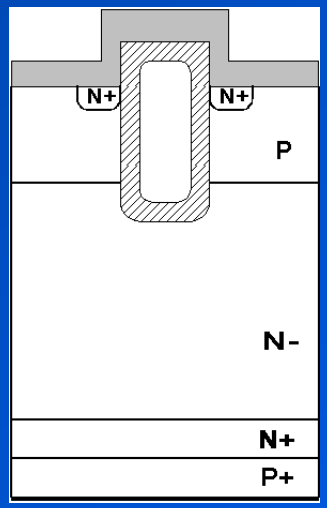


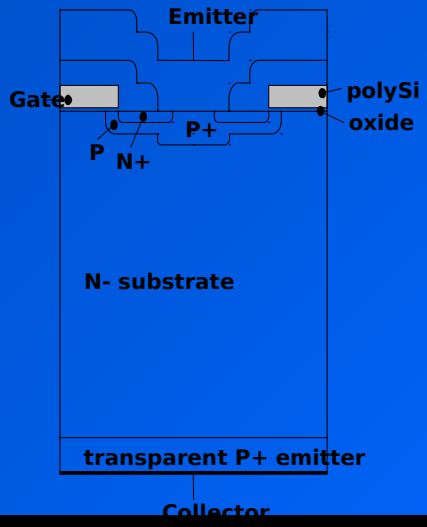
IGBT Models

In cooperation with Powerex, Inc.

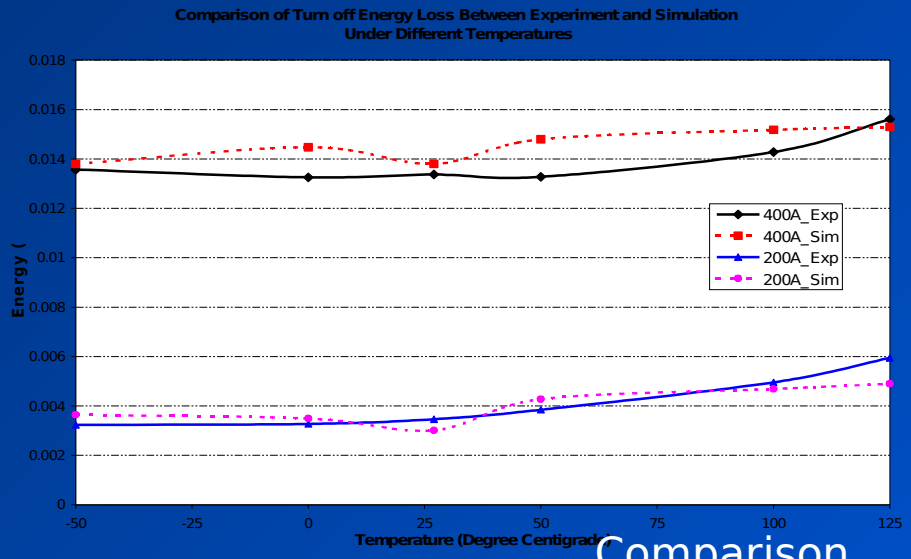
- Punch-through (PT), planar- and trench-gate.
- High-Voltage and Field-Stop Designs
- Non-Punch-Through



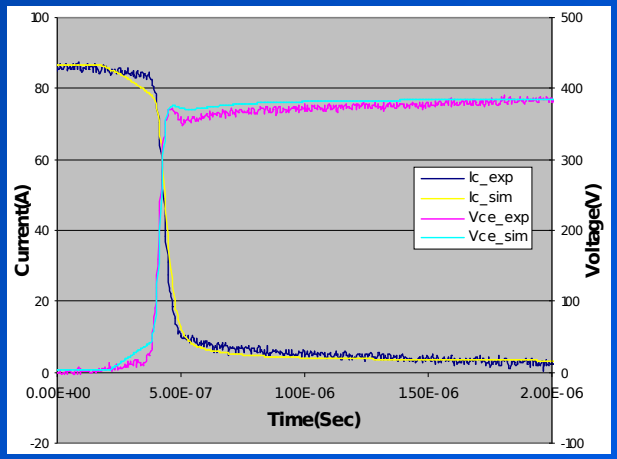




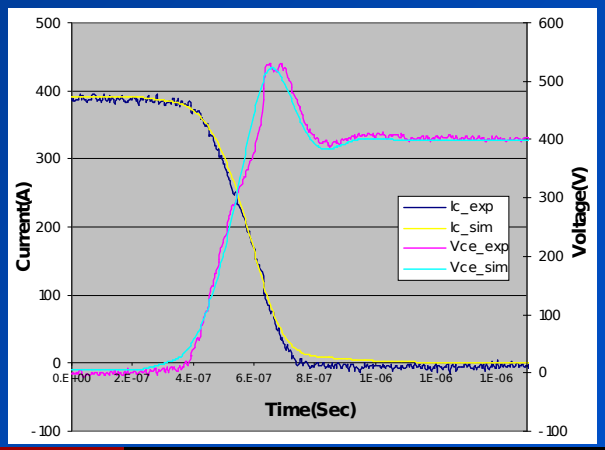
Validation of IGBT Models



Comparison between the experimental and simulation results for turn-off energy losses.



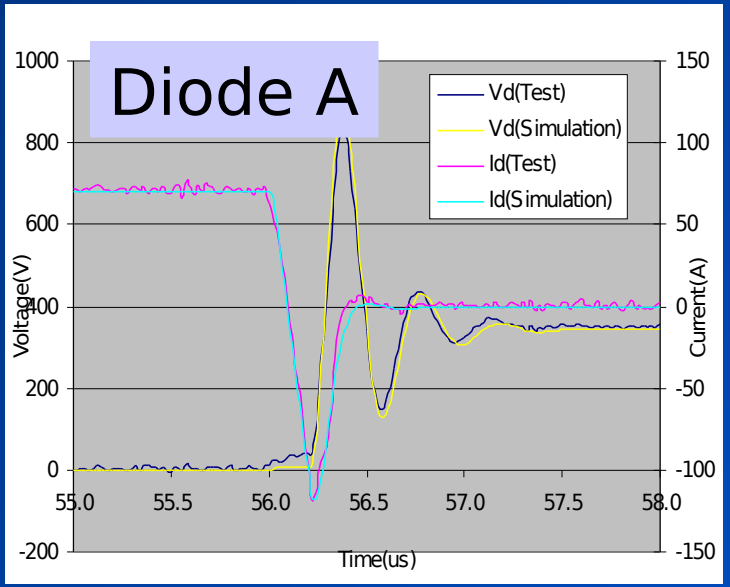
NPT-IGBT at -125 °C. Comparison between the experimental result (dark blue-current & pink-voltage) and simulation (yellow- current & light blue- voltage) during turn-off.

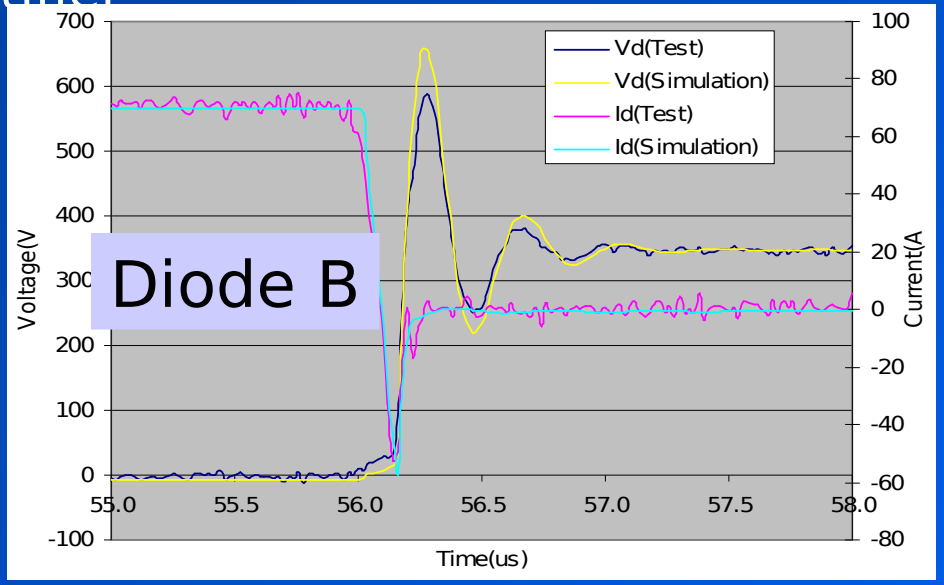


PT-IGBT at 100 °C. Comparison between the experimental result (dark blue-current & pink-voltage) and simulation (yellow-current & light blue- voltage) during turn-off.

Diode Characterization and Modeling

In cooperation with International Rectifier





Room temperature. Comparison between the experimental result (dark blue-voltage & pink-current) and simulation (yellow-voltage & light blue-current) during turn-off.

Diode	I_{FM} (A)	V_{RRM} (V)	R_{on} (mΩ)	V_{BR} (V)
A	100	600	17	900
B	81	1000	19	1500

Research In Control Systems

- Study applicability of controls based on methods such as “synergetic” and “immersion and invariance”, and develop tools for same
- Formalize methods for rapid control prototyping within VTB environment
- Develop controls for advanced machines
- Develop strategies for controlling local systems of competing loads, using communicative- and agent-based methods
- Perform simulation-based testing of human interfaces for shipboard power systems

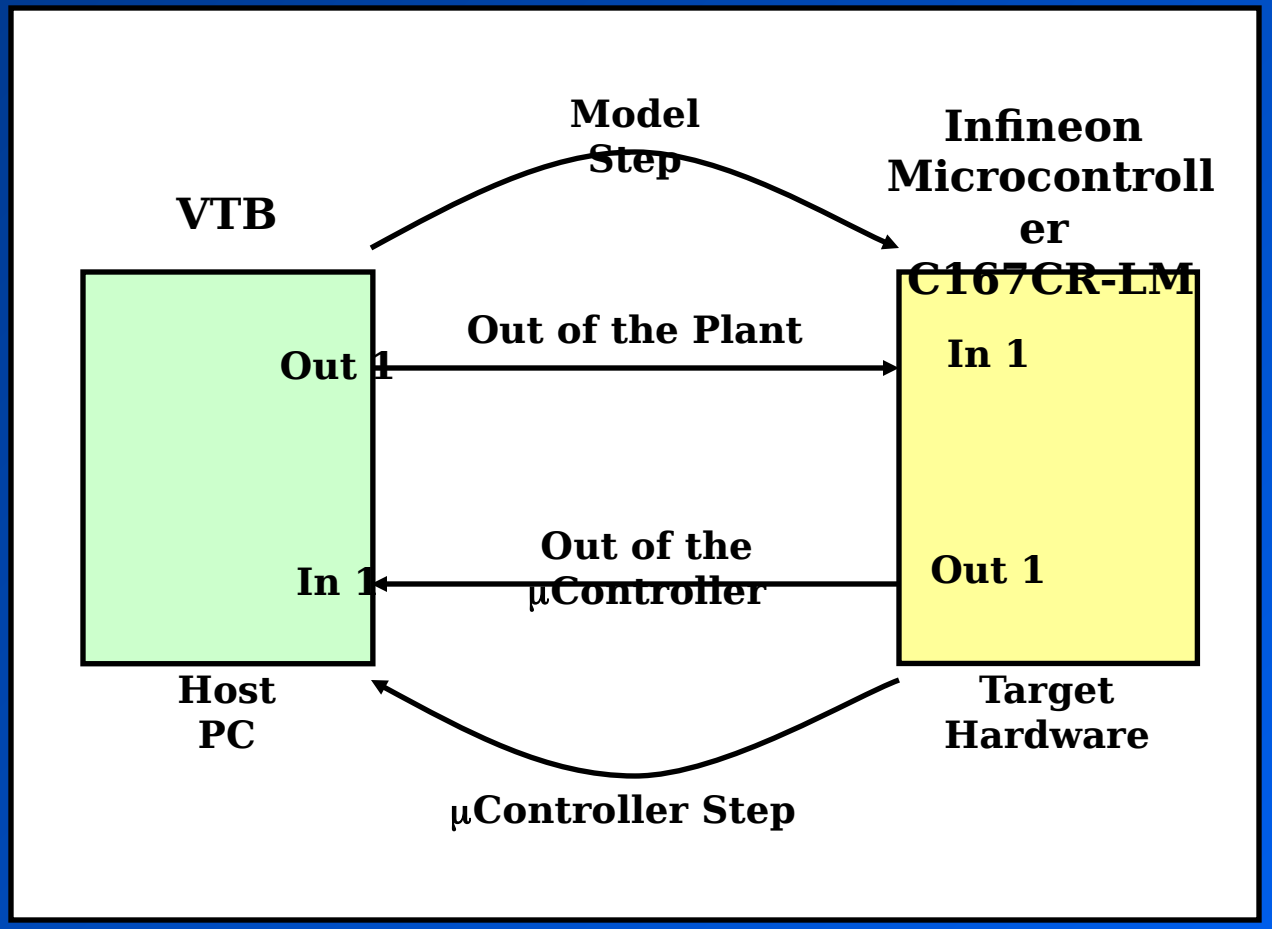
Methodologies for Rapid Control Prototyping

- Interfacing VTB with Real-time platforms (such as dSpace HW, Infineon Processor, TI-DSP)
- Giving users methodology for risk-free control testing
- Processor in the Loop (PIL)

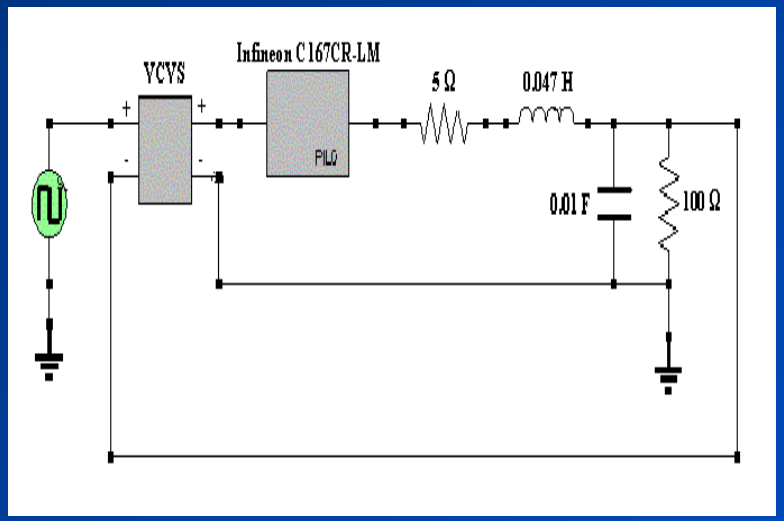
- PIL co-simulation is particularly useful for:
  - simulating
  - testing
  - and validating a controller algorithm

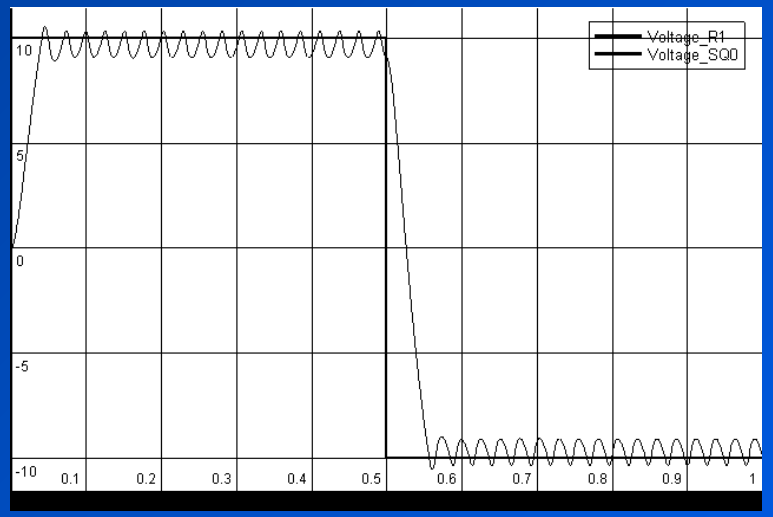
  In a system comprising a *plant* and a *controller*.
- PIL co-simulation provides an intermediate stage between simulation and deployment. The term "co-simulation" reflects a division of labor in which VTB models the plant, while code generated from the controller subsystem runs on the actual target hardware.

Interaction of plant and micro controller in a PIL co-simulation.



Example application





- Processor-in-the-loop test reveals problem …
- The output never reaches the steady state and the signal is ringing.
- The problem is resolved by realizing that the processor executes fixed-point (16 bit) math

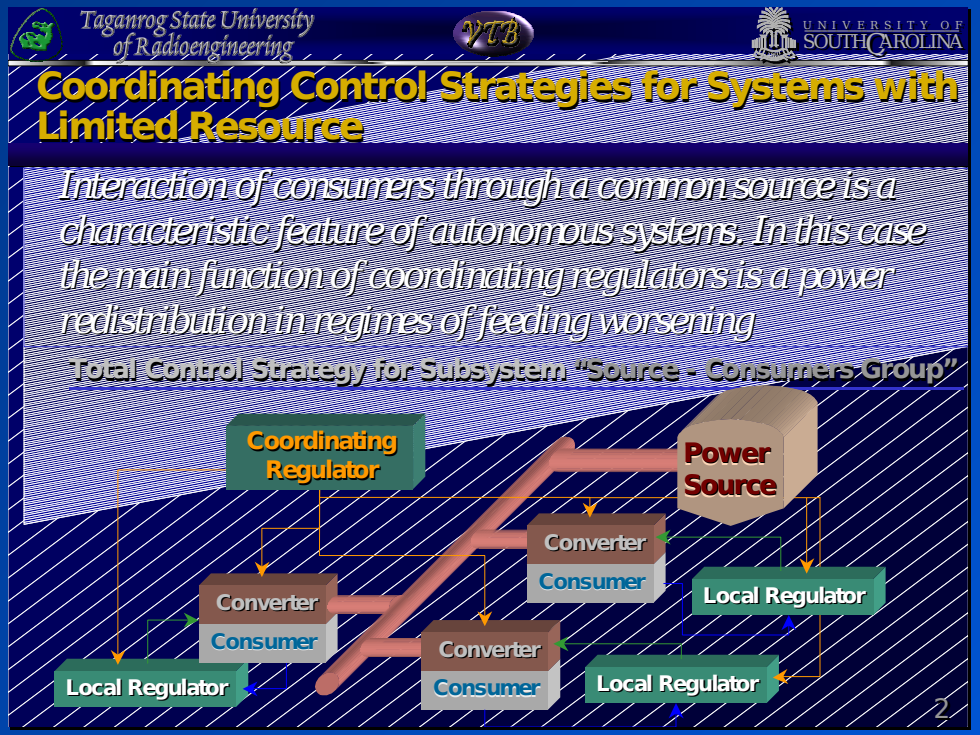
Wireless Extension of Processor In the Loop

- Wireless modem links the embeded μcontroller with VTB simulation

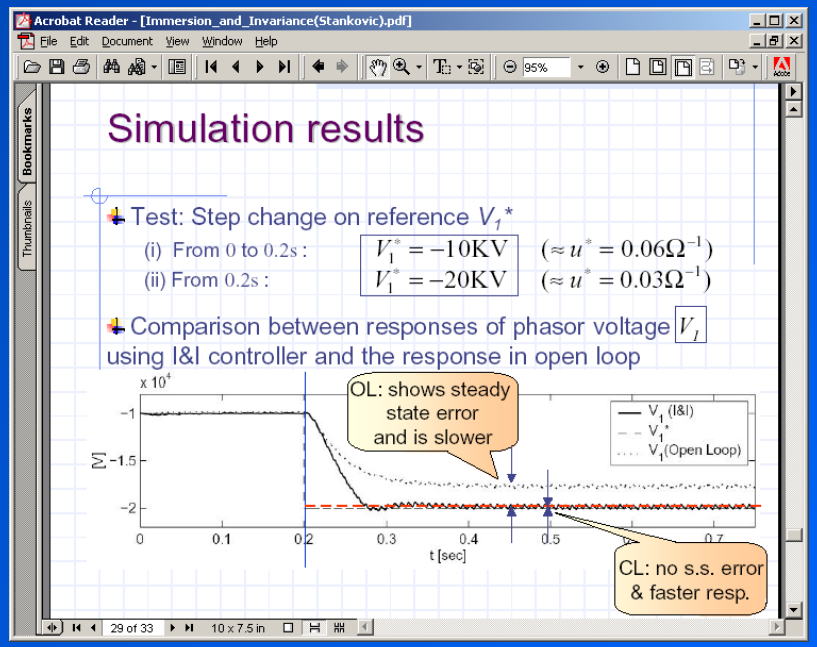
- Wireless link uses RS-232 connection, link is completely transparent to the computer and μC at both ends.

Control Methods

Synergetic Control
Kolesnikov, Taganrog Univ


Taganrog State University of Radioengineering
VTB
UNIVERSITY OF SOUTH CAROLINA
Coordinating Control Strategies for Systems with Limited Resource
Interaction of consumers through a common source is a characteristic feature of autonomous systems. In this case the main function of coordinating regulators is a power redistribution in regimes of feeding worsening
Total Control Strategy for Subsystem "Source - Consumers Group"
Coordinating Regulator
Power Source
Converter
Consumer
Converter
Consumer
Converter
Consumer
Local Regulator
Local Regulator
Local Regulator
2

Immersion and Invarianc
Stankovic, Northeastern


Acrobat Reader - [Immersion_and_Invariance(Stankovic).pdf]
File Edit Document View Window Help
Bookmarks
Thumbnails
Simulation results
Test: Step change on reference V_1^*
(i) From 0 to 0.2s : $V_1^* = -10\text{KV}$ $(\approx u^* = 0.06\Omega^{-1})$
(ii) From 0.2s : $V_1^* = -20\text{KV}$ $(\approx u^* = 0.03\Omega^{-1})$
Comparison between responses of phasor voltage V_1 using I&I controller and the response in open loop
x 10^4
OL: shows steady state error and is slower
V_1 (I&I)
V_1^*
V_1 (Open Loop)
t [sec]
CL: no s.s. error & faster resp.
29 of 33
10 x 7.5 in

Control Application Studies

- Synergetic Control for boost Converters
- Extension to multi-converter applications
- Sensorless control
- Testing Hybrid-Power Systems
- Future Energy Challenge 2003

Synergetic Control for Boost Converter

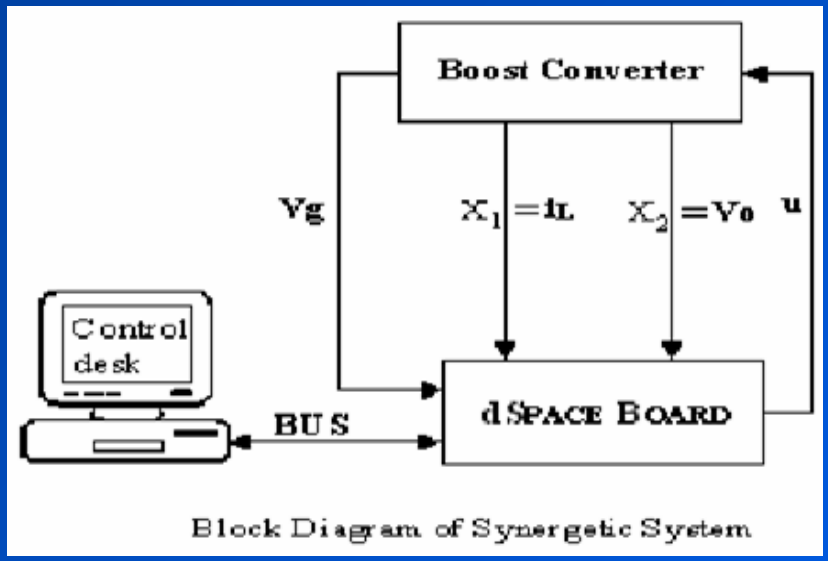
Approach

1. Theoretical analysis of the approach
2. Simulation in VTB and Simulink
3. Building a laboratory prototype of a simple boost converter
4. Testing the converter using synergetic control
5. Evaluate the results

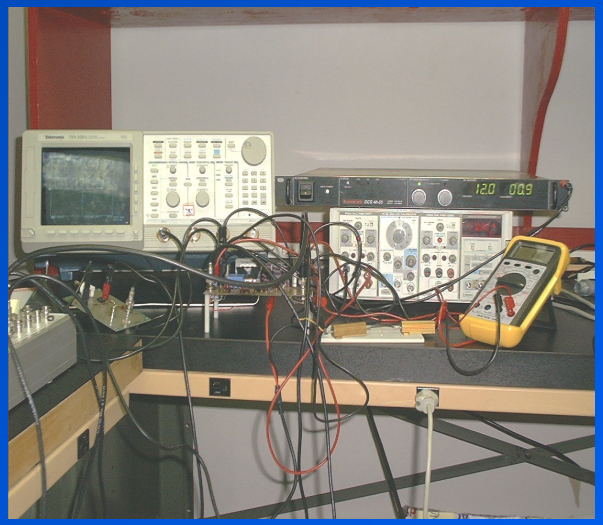
Advantages

- Based on the nonlinear converter equations : no small-signal linearization
- Fully analytical design procedure
- Potentially superior to the existing types of PID controllers for converters, with respect to their dynamic characteristics
- By selection of suitable macro-variables the designer can obtain interesting characteristics for the final system such as:
  - *Overall system stability*
  - *Parameter insensitivity*
  - *Noise suppression*

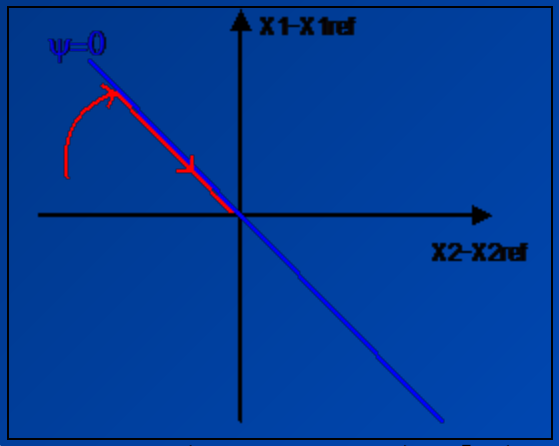
Hardware Testbed for Synergetic Control of Boost Converter



Block Diagram of Synergetic System

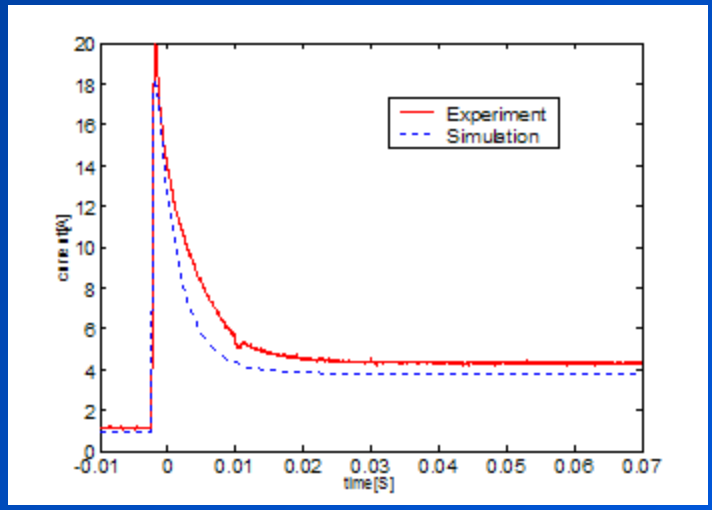


Simulation and Experimental Results

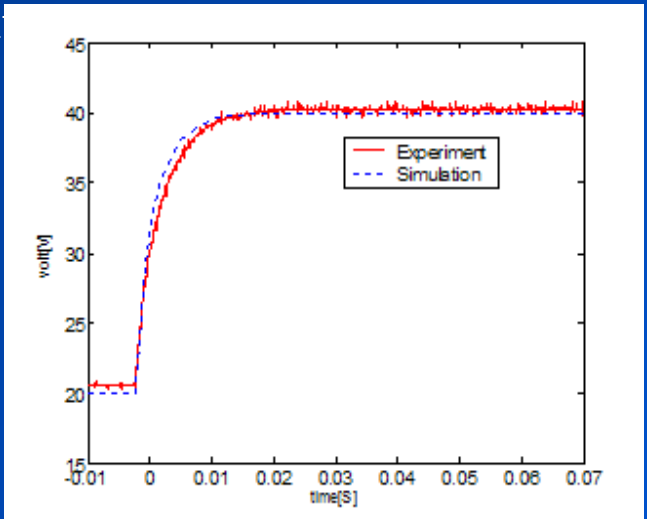


Control law $\psi = (x_2 - x_{2ref}) + k(x_1 - x_{1ref})$

Where X_1 inductor current, X_2 output capaci



Inductor Current



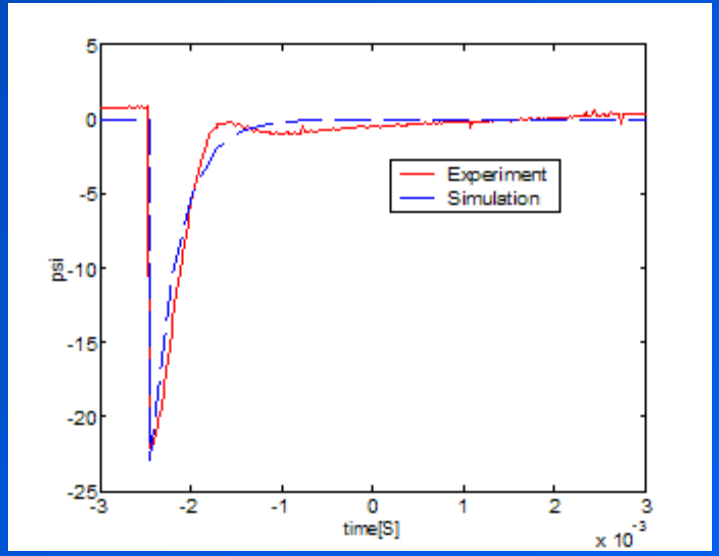
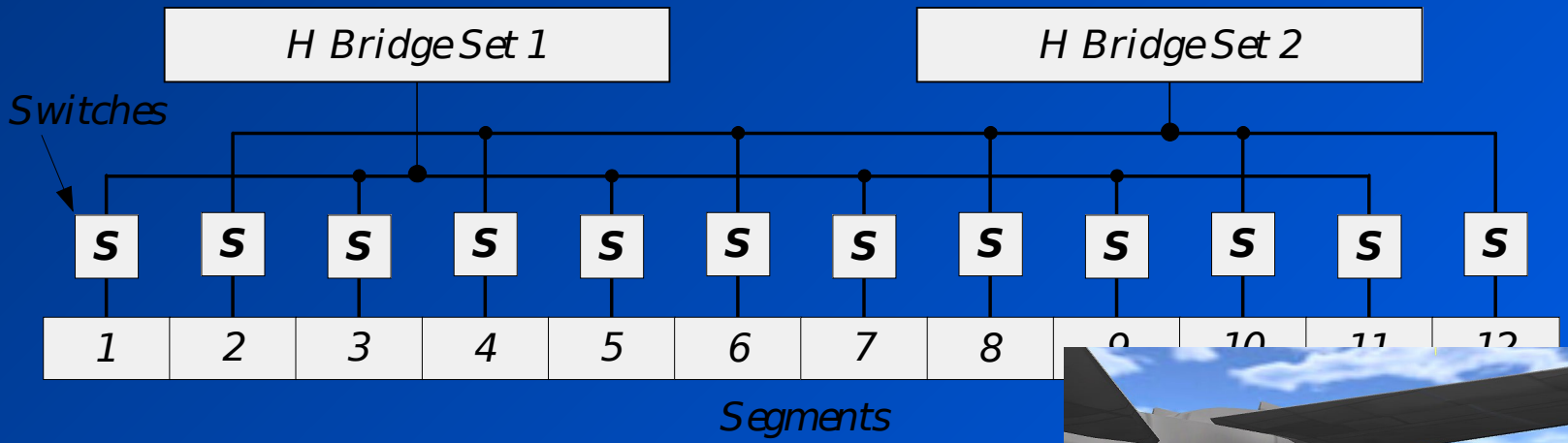


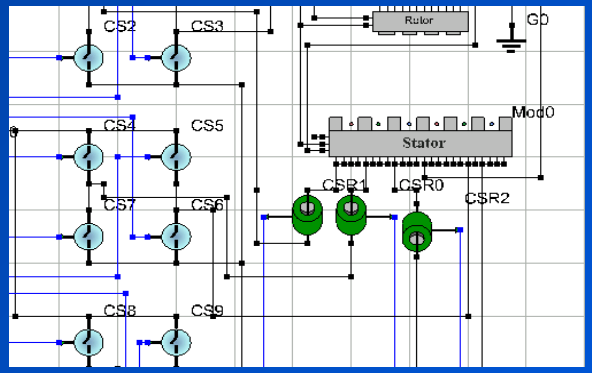
Fig 3 Output Voltage

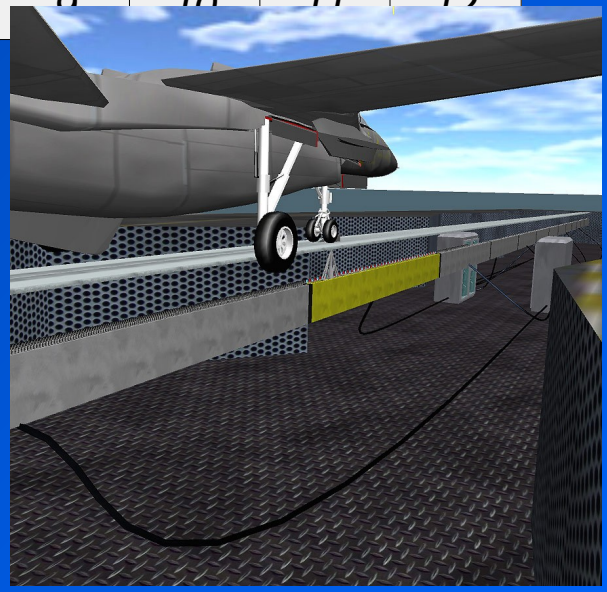
Fig 4 Magnetic Variable

Winding-oriented controls for modern machines

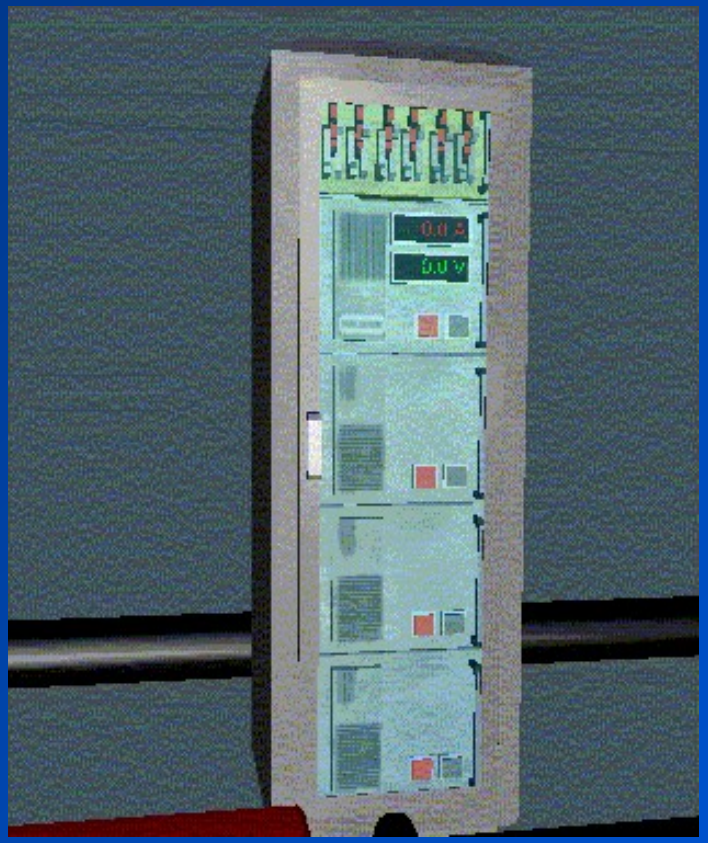


EMALS example





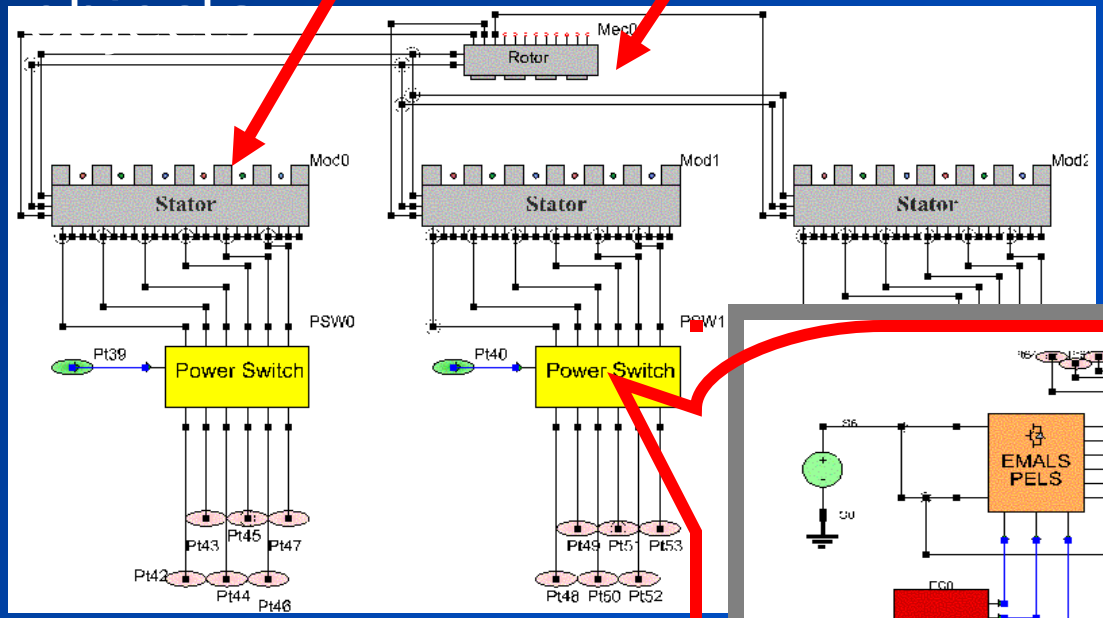
Human Interfaces for System Controls

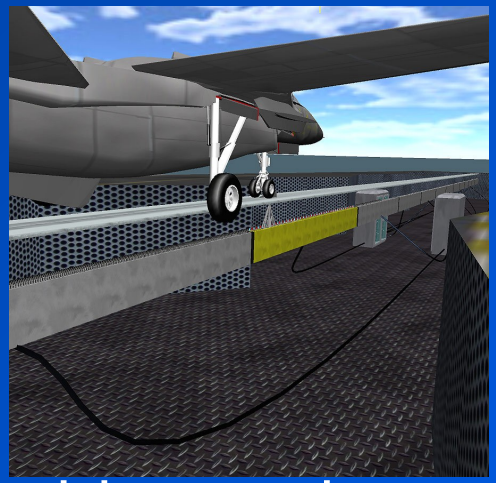


VTB Visualization Environment provides ideal environment to test user interaction with equipment, with full simulation support for system dynamics

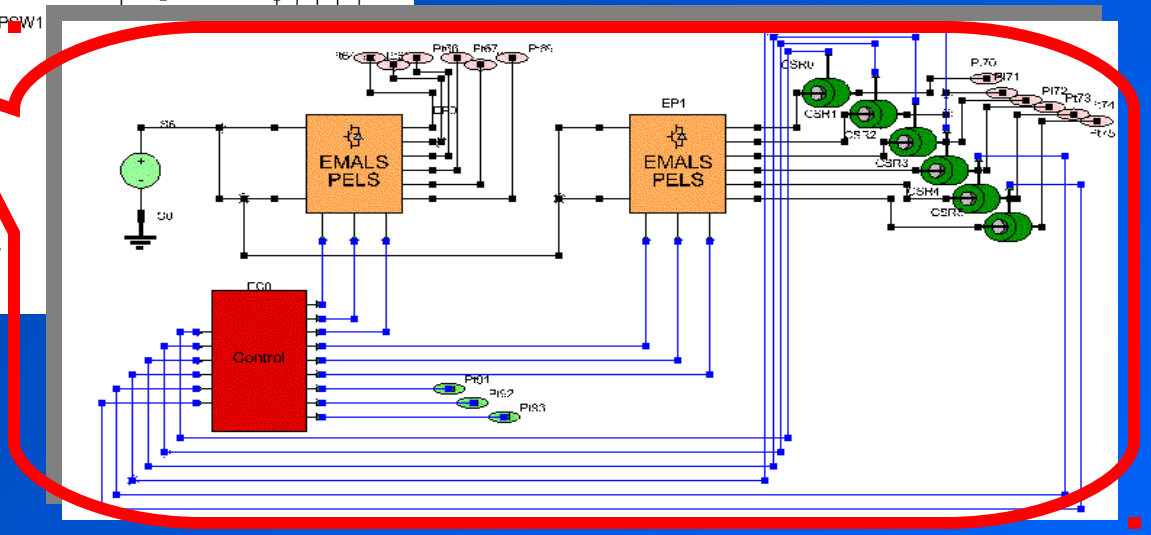
CONTROL of EMALS

Modular motor model with separate stator and slider

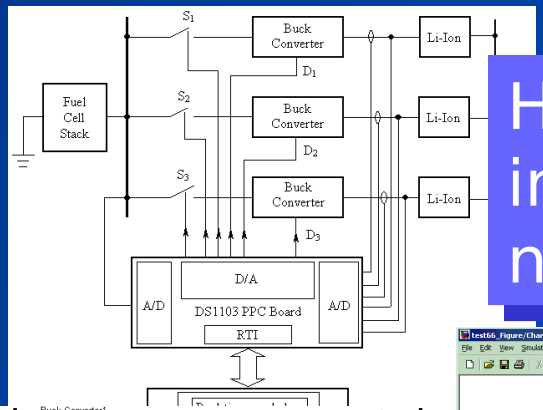




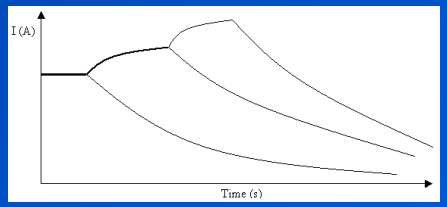
Switching and control network

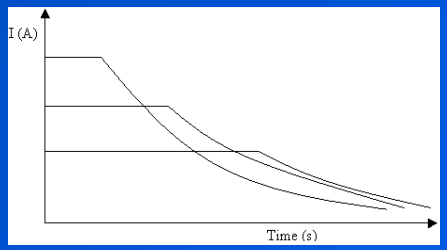


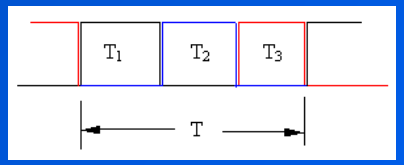
Example Application: Fuel cell powered battery charging station

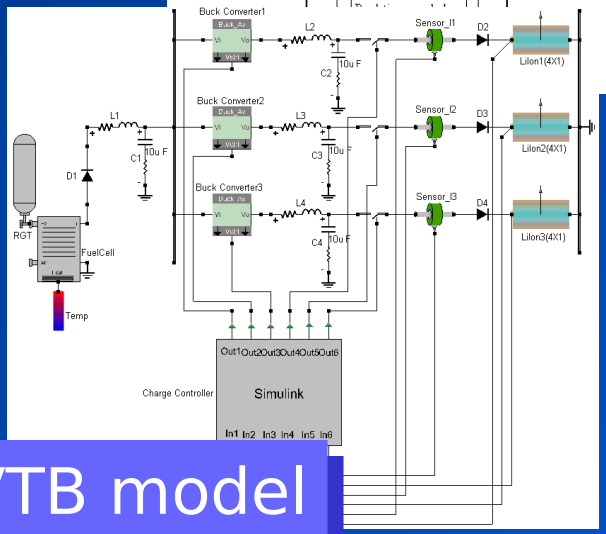


Hardware implementation

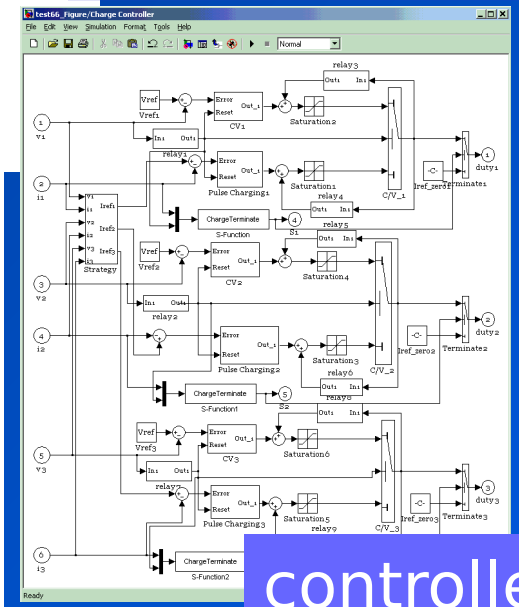








VTB model



controller

various charge current waveforms

Wavelet-based Controls

- Investigate the capabilities of
  - wavelet networks for adaptive control of non-linear systems
  - sub-band coding for VLSI-oriented control implementation
- Expected results
  - identification of strong and weak characteristics
  - evaluation of the trade-off between control benefits and complication of the algorithm
  - creation of VTB simulation blocks to facilitate the implementation of such controls

Wavelet-based Controls

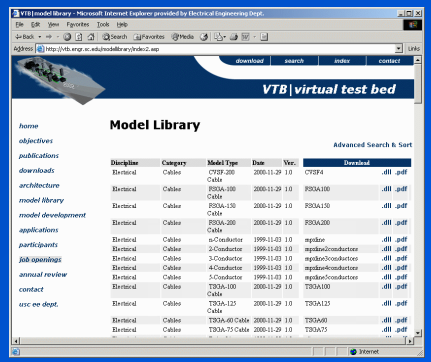
- Subsequent steps
  - literature overview
  - implementation of the algorithm in the VTB environment
  - simulation of a controlled electromechanical system
  - testing of the control algorithm on a physical electrical drive
- The problems encountered on the way will lead to
  - actual evaluation of the method
  - possible improvements

Summary

- USC participation in Electric Ship initiatives makes heavy use of the VTB environment
- Native strengths in power electronics, machines, power systems, and controls are applied to ship power systems
- Subcontracts support additional work including simulation, controls, visualization

VTB is Freely Available

- Download the software at http://vtb.engr.sc.edu/download
- Model library is online at http://vtb.engr.sc.edu/modellibrary new models every week



- Limited number of CDs available today
- Ver 1.61 available now
- Ver 2002 available now